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# THESIS

**AN EVALUATION OF THE BUDGET AND READINESS IMPACTS OF BATTLEGROUP SPARING**

by
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Battlegroup sparing is an inventory strategy that can significantly reduce the initial outfitting costs of a weapon system by greatly reducing the range and depth of spares required to outfit individual ships. This strategy moves low demand items from shipboard spare part inventories to intermediate level inventories which support an entire battlegroup. This thesis extends the techniques of Readiness Based Sparing (RBS) and proposes a method for defining suites of spares at both the shipboard and battlegroup level which augment each other to achieve a desired level of system readiness while realizing the efficiencies of battlegroup sparing To evaluate the impacts of this strategy, this thesis develops a computer simulation, which can be utilized to evaluate the budget and readiness impacts of applying this or any other inventory strategy to a weapon system. The methodology proposed by this thesis was then applied to the Cooperative Engagement System (CES), reducing initial outfitting costs by nearly 50%, an overall savings of over thirty million dollars in scarce outfitting funds.

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**AN EVALUATION OF THE BUDGET AND READINESS IMPACTS OF BATTLEGROUP SPARING**

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Submitted in partial fulfillment of the
requirements for the degree of

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# ABSTRACT

Battlegroup sparing is an inventory strategy that can significantly reduce the initial outfitting costs of a weapon system by greatly reducing the range and depth of spares required to outfit individual ships. This strategy moves low demand items from shipboard spare part inventories to intermediate level inventories which support an entire battlegroup. This thesis extends the techniques of Readiness Based Sparing (RBS) and proposes a method for defining suites of spares at both the shipboard and battlegroup level which augment each other to achieve a desired level of system readiness while realizing the efficiencies of battlegroup sparing. To evaluate the impacts of this strategy, this thesis develops a computer simulation, which can be utilized to evaluate the budget and readiness impacts of applying this or any other inventory strategy to a weapon system. The methodology proposed by this thesis was then applied to the Cooperative Engagement System (CES), reducing initial outfitting costs by nearly 50%, an overall savings of over thirty million dollars in scarce outfitting funds.

## THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

# TABLE OF CONTENTS

## LIST OF SYMBOLS, ACRONYMS AND ABREVIATIONS

| | |
|---|---|
| Ao | - Operational availability |
| AAW | - Anti-Air Warfare |
| ACIM | - Availability Centered Inventory Model |
| ARP | - Alternating Renewal Process |
| BSSM | - Battlegroup Sparing Simulation Model |
| CES | - Cooperative Engagement System |
| CNO | - Chief of Naval Operations |
| GE | - Gross Effectiveness |
| LRG | - Logistics Review Group |
| LRU | - Lowest Replaceable Unit |
| MLDT | - Mean Logistics Delay Time |
| MSRT | - Mean Supply Response Time |
| MTBF | - Mean Time Between Failures |
| MTTR | - Mean Time To Repair |
| NAVSEA | - Naval Sea Systems Command |
| NAVSEALOGCEN | - Naval Sea Logistics Center |
| NAVSUP | - Naval Supply Systems Command |
| RBD | - Reliability Block Diagram |
| RBS | - Readiness Based Sparing |

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# EXECUTIVE SUMMARY

Since the establishment of operational availability as the Navy's uniform measure of material readiness, the logistics community has made dramatic changes in the methodology used to determine the range and depth of spare parts carried onboard ships. Readiness Based Sparing (RBS) is currently the accepted method of achieving operational availability goals at the minimum cost.

Traditionally, the Navy has optimized its spare part inventories on a ship-by-ship basis, due to the independent nature of ship operations. Dramatically improved information systems and logistics channels that provide rapid support to deployed ships have reduced the logistics response time seen by independently operating ships. The steady decrease of spares budgets and this reduced logistics response time has lead to the Navy's exploration the application of multi-echelon sparing techniques to shipboard spares inventories

Battlegroup Sparing is a multi-echelon sparing technique which decreases the spares requirements of individual ships by providing in-theatre support of the typically high cost, low demand items that are currently forced aboard ships by RBS to attain operational availability goals set by weapon system program sponsors. Prior to this thesis, this concept was untested as the models currently used in RBS (ACIM and Tiger) cannot handle a multi-ship environment. This thesis developed the Battlegroup Sparing Simulation Model (BSSM) which provided a means for evaluating the impacts of multi-echelon sparing techniques in a shipboard environment.

In conjunction with BSSM, this thesis also developed a methodology which could be used for determining the proper range and depth of spares to maximize the savings of a multi-echelon sparing approach. This methodology, when used on the Cooperative Engagement System (CES), produced a range and depth of spares that achieved a given operational availability goal at less than fifty percent of the cost of the traditional method. If applied by the CES program office, this method could result in savings of over $30 Million to the Navy's initial outfitting funds.

# I. INTRODUCTION

## A. BACKGROUND

The Chief of Naval Operations (CNO) has cognizance over the U.S. Navy's acquisition programs. It exercises this authority through various program offices that manage the acquisition and lifecycle support of the U.S. Navy's weapon systems. Prior to the early 1980's, these program offices lacked a common approach to setting material requirements, which was noted by the CNO's Logistics Review Group (LRG) as a primary cause for the decreasing state of readiness of the weapon systems of the day. The LRG found that these "programs generally lacked any substantive link between readiness requirements, the reliability levels specified by contract, and their logistics resources and planning necessary to achieve the required readiness in the Fleet." [Provisioning and Fitting Out Support Manual] In response to these findings the CNO published OPNAV Instruction 3000.12 which, among other things, established Operational Availability (Ao) as the single measure of readiness for U.S. Navy weapon system programs. Ao is defined in this instruction as "the probability that the system is ready to perform its intended function in its operational environment when called for at any point during a mission." [OPNAVINST 3000.12]

The establishment of Ao as the uniform measure of material readiness forced the U.S. Navy to make dramatic changes in the methodology used to determine the range and depth of spare part inventories held onboard its ships.[1] Inventory models used prior to this period were primarily demand based with the goal of maximizing supply

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[1] In this thesis, spare part inventories held onboard ships will be referred to as "allowed items" or "allowance list items."

effectiveness; unfortunately supply effectiveness was not uniformly defined and could not be directly related to Ao.

To resolve this problem the U.S. Navy developed the Availability Centered Inventory Model (ACIM). Utilizing Equation (1.1), the model relates a supply system metric, Mean Logistics Delay Time (MLDT), to system readiness.[2] ACIM assumes the design of the system is fixed which allows it to consider MTBF and MTTR as constants, maximizing system readiness by minimizing MLDT.

$$Ao = \frac{MTBF}{MTBF + MTTR + MLDT} \quad (1.1)$$

During the period that ACIM was being created, the Naval Sea Systems Command was developing the Tiger model. This model accounts for the structure and intended mission cycle of a weapon system, then utilizes a Monte Carlo simulation to make Reliability Maintainability and Availability (RMA) assessments of that system. Of particular interest to the logistics community was the ability of the Tiger model to assess the readiness of a system for a given inventory's Gross Effectiveness[3] (GE).

The weaknesses of ACIM, which will be discussed further in Chapter III, and the availability of the Tiger model lead to the development of the Readiness Based Sparing (RBS) methodology, which is presently used by the U.S. Navy and the Department of Defense (DOD) as a whole. RBS is "the establishment of an optimum range and quantity of spares and repair parts at all stockage and user locations in order to meet approved,

[2] The terms of equation 1.1 will be discussed further in Chapter 2.
[3] An inventory's Gross Effectiveness is the probability that the required part is available from the ship's inventory given a system has experienced a failed component.

quantifiable, weapon system readiness, operational availability, or fully mission capable objectives." [DOD Directive 4140.1R]

The Naval Supply Systems Command established procedures for applying RBS and created a PC based workstation to allow weapon system program managers to apply RBS techniques to their specific weapon systems. The workstation uses a combination of ACIM and Tiger. ACIM is used to determine the order in which spares are added to the ship's allowance list while Tiger is used to evaluate the system readiness achieved by a given level of sparing.

The process begins by establishing bounds for the system Ao by first running the Tiger model with zero spares on board (0% GE) to deduce the system's zero spares availability ($A_z$). This is followed by a run with an unlimited amount of spares onboard (100% GE) to deduce the system's inherent availability $A_i$. ACIM and Tiger are then linked together by the OPT program, which is used to rank potential spares in order of their contribution to system Ao. This data is used to create the OPT listing which is a listing of individual parts and their unit cost in order of their contribution to system readiness. This listing can then be used to create the budget-to-readiness curve. Figure 1.1 is an example of a typical budget-to-readiness curve. The shape of the typical budget-to-readiness curve makes intuitive sense as one would expect to see decreasing marginal returns as inventory investment increases. The marginal analysis technique used by RBS has a tendency to select inexpensive items prior to expensive items, since they tend to make a higher contribution to readiness per dollar spent. Thus the upper portion of the budget-to-readiness is typically made up of high cost, highly reliable spare parts.

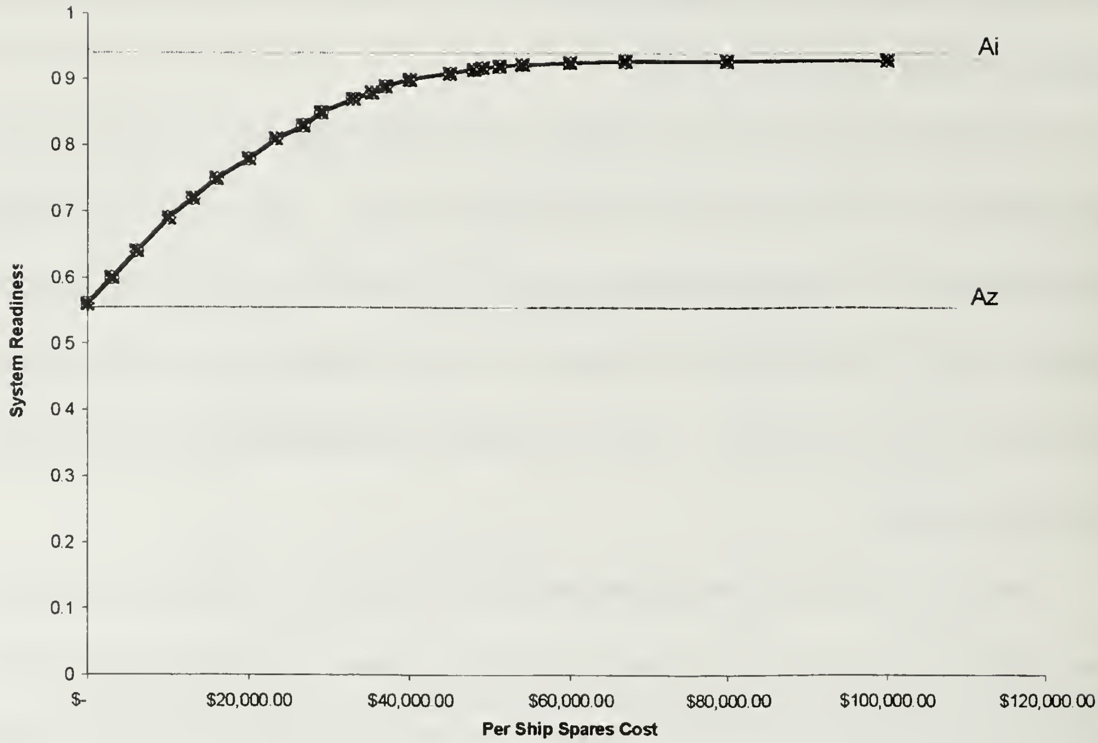


**Figure 1.1 A Typical Budget-to-Readiness Curve**

## B. PROBLEM STATEMENT

In today's atmosphere of declining DOD budgets and military downsizing, it does not make sense to continue to spend scarce inventory dollars on these expensive spare parts that are not likely to fail. Recognizing this potential cost savings, a multitude of naval studies over the past decade have yielded impressive cost savings by removing these highly reliable, but expensive items from shipboard inventories. However they have a common consequence: the ship can no longer realize required Ao goals.

One concept that is currently under consideration by the Naval Supply Systems Command and many weapon system program managers is Battlegroup Sparing. Battlegroup Sparing places those highly reliable but expensive items in a central location to support an entire battlegroup. This concept remains undeveloped, as there is currently no means to evaluate the impact on readiness of this type of sparing. The purpose of this thesis is to further explore the concept and to develop an algorithm and simulation program to evaluate the potential cost savings and readiness impact of Battlegroup Sparing.

## C. METHODOLOGY

To evaluate the impact of Battlegroup Sparing it was first necessary to create a model that could simulate a battlegroup of ships, each possessing a given set of weapon systems. The weapon systems on these ships would not only be supported by the ship's own inventory, but also by an intermediate level of supply that was drawn upon by all ships in the battlegroup. The purpose of the model is to determine the rate at which the battlegroup spares are depleted considering that all ships in the battlegroup were competing for the same spares, and the impact of the depletion rate on the readiness of the individual ships. For this reason the Battlegroup Sparing Simulation Model (BSSM)[4] was written.

Following the creation of the BSSM, the next step was to select a weapon system to explore the concept of Battlegroup Sparing. To following criteria were developed to maximize the potential benefits:

1. RBS data for the system must currently exist.
2. Systems should be common across many different ship types.
3. System should be highly reliable with flat budget-to-readiness curves.

[4] This model will be discussed in greater detail in Chapter IV.

The Cooperative Engagement System (CES) was a weapon system that met all of the above criteria and was also early enough in the acquisition process for this study to influence its initial outfitting requirements prior to their acquisition. These factors made it the obvious choice for this study.

The standard RBS methodology was then used to develop a listing of shipboard spares to determine the per ship outfitting cost of traditional methods. An OPT list was also created to determine the order which these spares would be moved to the intermediate level during the experiment. The battlegroup simulation was then run several times. At each iteration, an additional spare was moved from the shipboard inventory to the intermediate inventory, reducing redundant inventory in the battlegroup. The result of this process was a new budget-to-readiness curve that considers the entire battlegroup. This curve was then used to draw conclusions on the budget and readiness impacts of battlegroup sparing.

## D. THESIS STRUCTURE

The organization of the remainder of this thesis is as follows. Chapter II will discuss readiness concepts and relate them to the Cooperative Engagement System (CES). Reliability Block Diagrams (RBD's) will then be discussed and the CES will be broken down into its RBD. Chapter III will discuss the elements of RBS, the RBS workstation and the weaknesses of RBS as it is currently used. Chapter IV will describe the BSSM and the methodology used to validate it. Chapter V will describe the method of combining the RBS process with the BSSM, using the CES. Finally, Chapter VI will discuss the conclusions and recommendation that stem from the results of this study.

# II. READINESS CONCEPTS

## A. OVERVIEW

The readiness of a system is a function of that system's reliability, maintainability and supportability. These terms are defined as follows [Provisioning and Fitting Out Support Manual]:

- Reliability is the duration or probability of failure free system performance under a given set of conditions.
- Maintainability is the ability of an item to be retained in or restored to a specified operating condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.
- Supportability is the effectiveness of the logistics support provided for a weapon system. It represents the remaining downtime where no active maintenance (including fault isolation) is being performed.

A system's Mean Time Between Failures (MTBF) is the average time between successive failures, which equates to system reliability. A system's Mean Time To Repair (MTTR) is the average time required to repair a system in its operating environment (when necessary resources are available); equivalent to system maintainability. The final factor of system readiness, system supportability, is equivalent to the system's Mean Logistics Delay Time (MLDT) which is the average time delay caused by the logistics support system [OPNAVINST 3000.12].

Having defined each of the terms found in Equation (1.1), the relationship between system readiness and that system's reliability, maintainability and supportability is now more clearly defined. Given this relationship and a stable design, the logistician is responsible for determining the appropriate sparing levels to reach the system's readiness goal at minimum cost. Since reliability and maintainability are primarily functions of system design, which has been fixed, MTBF and MTTR are considered to be constants. This leaves MLDT as the only variable in Equation (1.1) that can be varied to influence system readiness. ACIM minimizes MLDT for a given budget constraint to optimize onboard stock levels. Although this method gives a good solution to the inventory problem, it assumes that all parts are of equal importance to the reliability of the system, which is not the case.

## B. RELIABILITY BLOCK DIAGRAMS

Reliability Block Diagrams (RBD's) are a means of considering the importance of a part to the reliability of the system. "An RBD is a logic diagram which, by means of the arrangement of blocks and lines, depicts the effect of an item failure on a system's functional performance." [Reliability Block Diagram Standard, May 1987] The process begins by breaking the system down into a set of blocks, which represent the set of functions it is required to perform. Each block is then broken down further into blocks that represent sub-functions of the block. The process continues until a Lowest Replaceable Unit (LRU)[5] is reached. When the system has been fully broken down, each of the original blocks is represented by a series of block diagrams that represent the sub-functions and LRU's of that block. Figures (2.1) through (2.3) depict this hierarchy for a notional aircraft system. At the top level, Figure (2.1), the system has six blocks; an airframe, an avionics suite, two engines and two hydraulic systems. Figure 2.2 is a

[5] An LRU is a component of the system that can be removed and replaced by shipboard personnel. Each LRU in the system is a candidate for an onboard spares allowance.

breakdown of engine #1, and Figure 2.3 is a breakdown of fuel system #1. The fuel nozzle and fuel pump would be considered to be LRU's of this aircraft system.

Once the supporting documentation for each of the original blocks has been completed, the blocks are connected with a reliability line. This line represents the interdependency between these equipments and the performance of the system. If this line is broken by a failed component the system will fail. The reliability line is in bold print in Figures 2.1 through 2.3.

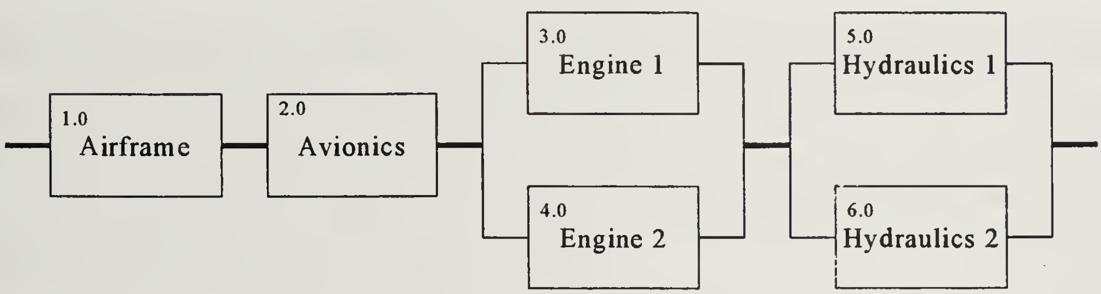


**Figure 2.1 Example Reliability Block Diagram (Upper Level)**

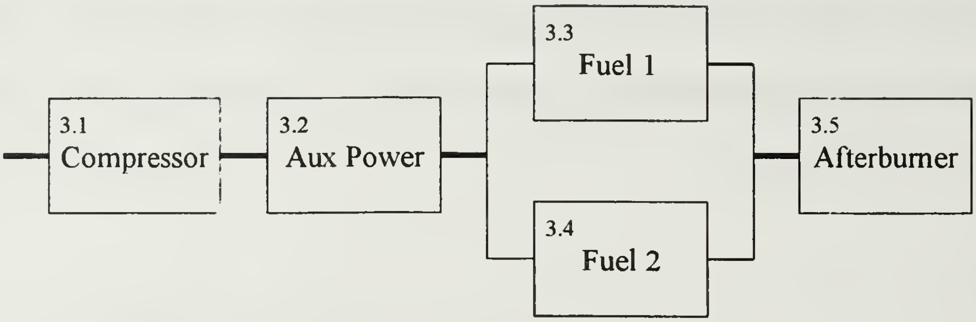


**Figure 2.2 Reliability Block Diagram**
**Block 3.0 (Engine #1)**

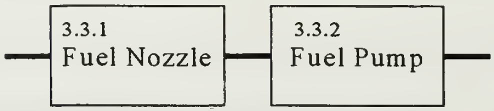


**Figure 2.3 Reliability Block Diagram**
**Block 3.3 (Fuel System #1)**

Once the blocks have been linked together by the reliability line the RBD is complete. Though omitted from Figures 2.1 through 2.3, data including the MTBF, MTTR and duty cycle of the equipment is then placed in each individual block. The RBS workstation, which will be discussed further in Chapter III, contains a utility called the

Computer Aided Readiness Assessment Tool (CARAT) which allows the workstation user to build RBD's and create input files reflective of this data for use in Tiger and ACIM.

## C. OPERATIONAL AVAILABILITY

The purpose of creating an RBD for the system is to allow the models to calculate system Ao. The definition given for Ao in the introduction of this thesis is useful in explaining the meaning of Ao, but does not provide an exact method to use when trying to actually calculate the Ao of a given system. An equivalent but more useful definition is "the percentage of time that a system is capable of performing its intended function." [Provisioning and Outfitting Support Manual, October 1995] Given the mission cycle of the system in question, uptime is defined as the amount of that time that the system is capable of performing its intended mission, while downtime is the amount of that time that the system is not capable. Using these definitions of uptime and downtime, Equation 1.1 can be simplified to Equation 2.1, which is used to calculate system Ao by the simulation models discussed in Chapters III and IV.

$$Ao = \frac{Uptime}{Uptime + Downtime} \qquad (2.1)$$

## D. COOPERATIVE ENGAGEMENT SYSTEM (CES)

The Cooperative Engagement System (CES) is designed to "significantly improve Battle Force Anti-Air Warfare (AAW) capability by coordinating all force AAW sensors into a single real-time fire control quality composite track picture." [CES Integrated Logistics Support Plan] The system consists of two major subsystems, the data distribution system (DDS) and the cooperative engagement processor (CEP). The DDS allows individual units to transfer battlefield information to one another via line of sight directional signal. The CEP is a common data process placed on all units that allows each unit to see essentially the same display of this data. Current plans are to install CES on 146 surface ships with initial installs beginning in mid FY-99. [Mr. Jeff Hoare, 13 Aug 97]

## E. APPLICATION OF RBD TO CES

The purpose of this thesis is to evaluate the consequences of applying battlegroup sparing to CES. The models that will be discussed in Chapters III and IV were used to make this evaluation, which required the development of an RBD for CES. The RBD of CES used for this thesis was created by NAVSEALOGCEN and is included as Appendix (A).

# III. READINESS BASED SPARING (RBS)

## A. OVERVIEW

The RBS process consists of three phases: Readiness Assessment, Sparing Determination and Life Cycle Maintenance. Though the phases are interrelated, this thesis is primarily concerned with the Sparing Determination phase. During this phase, Tiger and ACIM are used in conjunction with one another to determine the spares suite that achieves a desired level of system readiness at the minimum cost. The RBS workstation was created to allow program offices to perform RBS on their weapon systems. This workstation includes the ACIM, Tiger and OPT programs and an RBD building utility called CARAT.

## B. AVAILABILITY CENTERED INVENTORY MODEL (ACIM)

ACIM is "a stationary multi-echelon model based on Markov process and queuing theory." [Castillo, 1989] Though the model is capable of determining inventory levels at multiple echelons of supply, it is currently used only to determine consumer level inventories, which are those held onboard ships. ACIM makes the following assumptions:

1. External demands on supply are a stationary compound-poisson process.
2. An allowed item is reordered when issued from stock on a one-for-one basis.
3. Multiple locations of the same part are treated as unique items.
4. MTTR and MTBF are treated as constants.
5. Component (LRU) failures are independent.

Using these assumptions, ACIM calculates the contribution to readiness of each potential spare by dividing its Mean Supply Response Time (MSRT) by its unit cost. The MSRT for a given part is calculated by dividing the total expected logistics delay time by the number of requirements expected for that part.

For example, consider a component with a Mean Time Between Failures (MTBF) of 500 hours. There is currently 1 spare on the ship's allowance list and its parent system has a duty cycle of 2000 hours. The following is a calculation of the contribution to readiness of placing an additional spare of this item on the ship's allowance list.

$$B_i = \sum_{x>s_i} (x - s_i)p(x;\lambda_i T) \qquad (3.1)$$

$B_i$ = Expected number of backorders of item i at any point in time.
$s_i$ = Shipboard stock level of item i.
$\lambda_i$ = Daily demand rate for item i.
T = Stock protection period in days.
$P(x;\lambda_i T)$ = the probability of x demands given a failure rate of $\lambda_i$ during the time period T.

The calculation begins by utilizing Equation 3.1 [Naval Supply Systems Command, 18 October 1983] to calculate the expected number of backorders[6] of the item at any point in time. For this equation, the daily failure rate ($\lambda_i$) is calculated by multiplying the hourly failure rate of the component (1/MTBF) by the expected number of operating hours per day, which in this case is 24, thus $\lambda_i = 24/500 = 0.048$. The stock protection period (T) is equivalent to the Mean Requisition Response Time (MRRT); current policy is to set this value equal to 15 days, in accordance with supply system requisition processing standards. [NAVSEALOGCEN October 1995]

[6] In this context, a backorder is a requisition that has been referred off the ship to be filled by the wholesale supply system.

Assuming that demand is Poisson distributed, the probability that a given number of spares (x) is required during the stock protection period, $p(x;\lambda_i T)$, is calculated using Equation 3.2. Utilizing Equation 3.2, the probability that a second component is required in the 15-day stock protection period is 0.17532. Summing the terms of equation 3.1 for our example yields an expected number of backorders at any given time of 0.35. This figure is then multiplied by 2000 (duty cycle hours) to estimate the expected amount of cumulative time the item is on order from the ship yielding a result of 700 hours.

$$p(x;\lambda_i T) = e^{-\lambda_i T} \frac{(\lambda_i T)^x}{x!}, x = 0,1,2... \qquad (3.2)$$

Since the item's MTBF is 500 hours, the expected number of failures is 2000/500 = 4. The MSRT of the item can then by calculated by dividing cumulative backorder time by the number of failures. Since the expected cumulative amount of time the item is on order from the ship is 700 hours, the MSRT of the part would be 700/4 = 175 hours. If the cost of additional unit of the part was $500, the item would be given a score of 175/500 = 0.35.

This method is used on every component in the system to calculate the value of adding a spare of that component to the ship's allowance list. The component with the highest score is then chosen and a spare for that component is added to the ship's allowance list. The Gross Effectiveness (GE) figure for each equipment is then calculated by dividing the sum of its component's back orders ($B_i$) at any point in time by its total number of components. A more thorough description of the ACIM methodology can be found in the ACIM Handbook. [CACI Inc., May 1983]

Though an improvement over its demand based predecessors, ACIM has three major weaknesses. First and foremost is ACIM's consideration of every system as a series of components, which does not allow the model to account for the gain in reliability caused by components that are connected in parallel. The second weakness is that ACIM assumes failures to occur as a Markov process. This assumption causes a continuous failure process, which is unrealistic, as a failed component would have to spend some period of time being regenerated prior to returning to an operational status. The final weakness is that ACIM is based on steady state conditions, whereas an actual weapon system would never reach steady state due to its finite mission cycle.

## C. TIGER MODEL

Tiger is "a discrete, event-driven model which uses Monte Carlo techniques to estimate system parameters given the estimated MTBF and MTTR of the system components." [Castillo, 1989] The Tiger program was developed by NAVSEA to assess the reliability, maintainability and availability of navy weapon systems and continues to be used to make these evaluations throughout the lifecycle of the weapon system. The Tiger simulation requires the following as inputs:

- Mission Timeline
- System Equipments
- System Description
- Logistic Support

The mission timeline is determined by the program office and is calculated with respect to the Design Reference Mission (DRM) of the ship class on which the weapon system is to be placed. "The DRM defines the distinct mission phase types (e.g. in-port, cruise, engagements, etc...) that a particular ship class is expected to experience in wartime." [NAVSEALOGCEN, June 1996] These mission phase types are then input into Tiger as time sequences, which are used to build the simulation timeline.

The equipments of the system are defined in Tiger by the individual blocks of the system's RBD. Each block that represents an equipment is given discrete reliability (MTBF) and maintainability (MTTR) characteristics and the mission type phases for which it will be operational. The system description is made in Tiger by linking these blocks together and creating the RBD of the system. As discussed in Chapter II, the software utilizes the RBD to translate the structure of the system to computer readable code. This code allows the simulation to determine the state of the system (up or down) given a change in any one of its equipments.

The final input, logistics support, is provided by ACIM. Given a specified level of sparing, ACIM utilizes the method discussed earlier in this chapter to calculate the GE for each of the system's equipments. The equipment GE's are used by Tiger as the probability that, given a failure occurs that requires a spare part, that part is on the ship's allowance list and is currently available for issue.

Once the required information has been input, the operator can run the Tiger simulation. The simulation begins by scheduling the end of the first phase of the mission cycle. At this time the system will go through some type of change in the equipments that are required to maintain the system in an operational status for that mission cycle. A failure event is then scheduled for each of the equipments required by the first phase.[7] After these events have been scheduled, the mission cycle begins with all equipments in an "up" status. As equipment failures occur, repairs are made by first determining the logistics response time and then the time to repair. Drawing a random number between 0 and 1 determines the logistics response time; if the number is less than the GE for that equipment, the shipboard logistics delay of 2 hours is used. Otherwise, a logistics delay of 360 hours is used.[8] Once the logistics delay transpires, the time to repair is calculated by sampling from an exponential distribution with a mean equal to the MTTR of the equipment. After this time has elapsed, the equipment is scheduled to fail once again and is "turned on." This process continues throughout the mission cycle for those equipments required by the current phase. Once the mission cycle is complete the program is reset and run again, continuing in this manner until it reaches the number of iterations predetermined by the user. After all iterations are complete, Tiger computes system availability by dividing total system uptime over all trials by total time for all trials.

The major weakness of the Tiger model involves the number of iterations the model is run; there is no set policy for the user to determine this number. Current practice is for the user to estimate the number, run the model, then choose a higher number and run the model again. The user then compares the two results and determines

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[7] The time of the failure events are determined by sampling from an exponential distribution with a mean equal to the MTBF of the equipment.

[8] The logistics delays of 2 hours and 360 hours reflect goals the Navy has set for shipboard and wholesale supply response.

if the estimation of system availability has converged. This method provides no control for accuracy and no measure of the standard error of the results.

## D. OPT PROGRAM

The OPT program was developed by NAVSUP to integrate the use of Tiger and ACIM in the RBS workstation. The process begins by performing a set of Tiger runs for each of the individual equipments that make up the system. These runs are done to find the equipment Ao over the following range of GE figures: 0.0, 0.5, 0.75, 0.9 and 1.0. A cubic spline is then used to fit a curve through these points, which is called the selection curve for that equipment. The selection curves for a notional system consisting of two equipments (A and B) are depicted in figure 3.1.

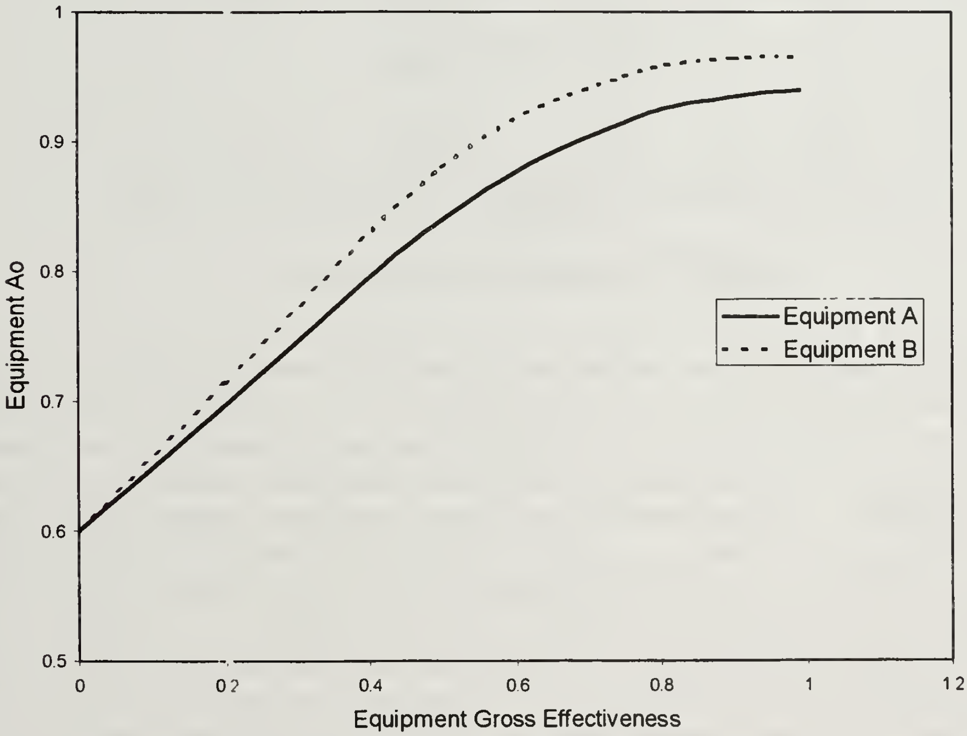


**Figure 3.1 Equipment Selection Curves**

In the next step of the process, ACIM is used to determine the order that spare parts will be added to the ship's allowance list. Utilizing the method discussed earlier in this chapter, ACIM considers each equipment independently, ranking its components in accordance with their individual contribution to equipment GE per dollar spent. The result being the creation of what is called the sparing index for that equipment. Table 3.1 is an example of a sparing index that would correspond to Figure 3.1. From this table, the addition of part number 2222A would increase equipment A's GE from .205 to .396.

| Equipment A | | Equipment B | |
|---|---|---|---|
| Component | GE | Component | GE |
| 1111A | .205 | 1111B | .425 |
| 2222A | .396 | 2222B | .585 |
| 3333A | .485 | 3333B | .695 |

**Table 3.1 Equipment Sparing Indices**

Once the selection curves and sparing indices have been developed, an iterative process begins. For the first step, only the highest-ranking component on each sparing index is considered. The improvement that these components makes to their parent equipment's Ao is then computed, the one resulting in the greatest improvement is then added to the shipboard allowance list. For example, using the data from Table 3.1, the addition of part 1111A improves equipment A's GE to .205, which corresponds to an Ao increase of 0.1 (0.6 to 0.7). The addition of component 1111B improves equipment B's

GE to .425, which corresponds to an Ao increase of 0.15. This can be seen graphically in Figure 3.2.

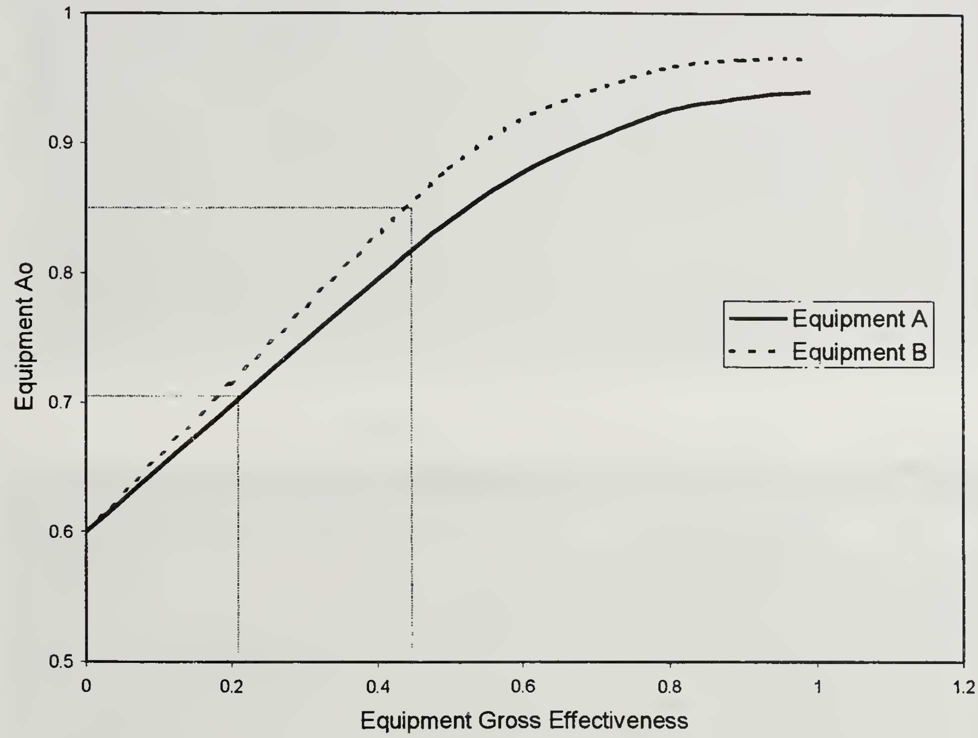


**Figure 3.2 Component Comparison on Equipment Selection Curves**

From our example, component 1111B would be chosen as it yields the greatest improvement in equipment Ao. The next step is to use Tiger to calculate the system Ao given that component 1111B is allowed onboard. If the system's Ao goal is not met, the equipment Ao improvement from the next ranking component on equipment B's sparing index (2222B in our example) would be compared to the improvement for equipment A that was found in the previous comparison. The process continues until the calculated Ao of the system becomes asymptotic to the system's inherent availability.

## E. RBS WORKSTATION

The RBS workstation is the operating environment created by the NAVSUP to give program offices a user-friendly environment to determine sparing levels for their weapon systems. The RBS workstation is a DOS-based software package that can be run on any PC. The ACIM and OPT programs are run from the retail allowance menu while Tiger is run from the readiness menu, as shown in Figures 3.3 and 3.4.

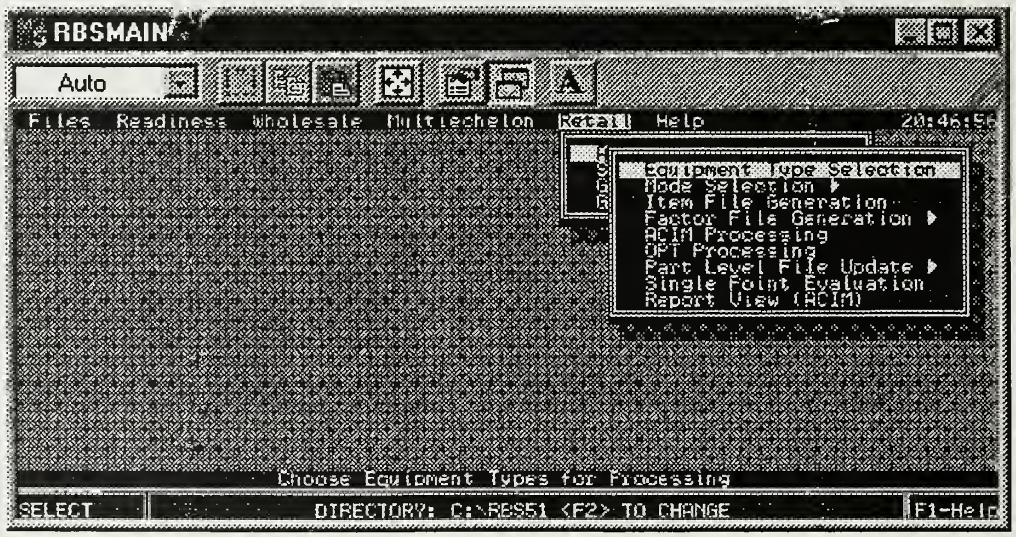


**Figure 3.3 Retail Allowance Menu**

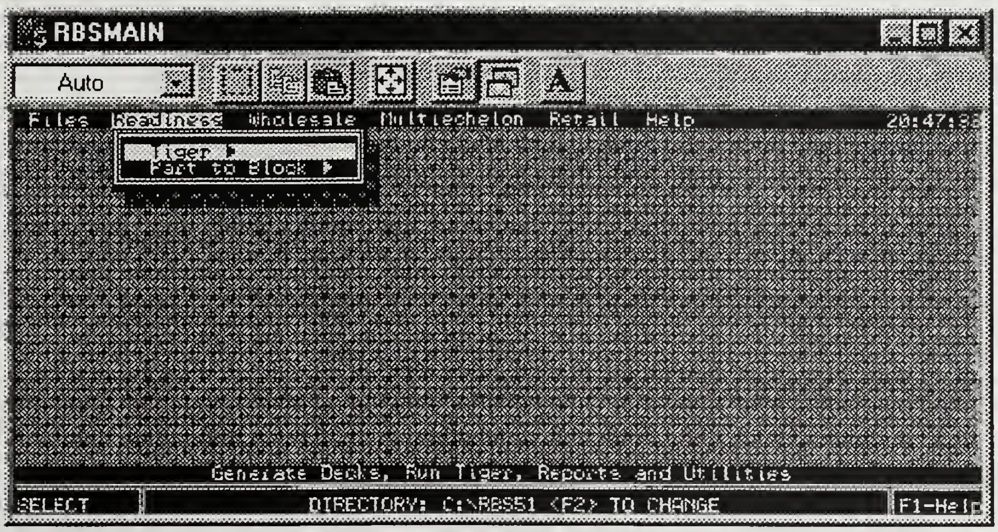


**Figure 3.4 Readiness Menu**

The RBS workstation also comes with a utility called the Computer Aided Readiness Assessment Tool (CARAT). CARAT is a Graphical User Interface (GUI) that allows the user to develop RBD's and their corresponding Tiger and ACIM input files, the CARAT user environment is depicted in Figure 3.5. All NAVSEA/SPAWAR programs that require RBS sparing levels currently use the RBS workstation.

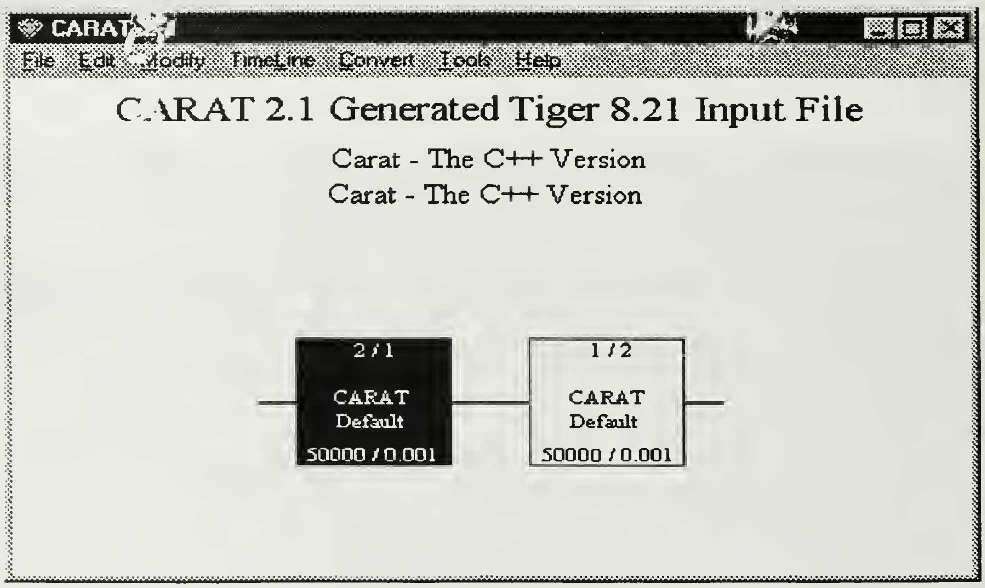


**Figure 3.5 CARAT User Environment**

# IV. BATTLEGROUP SPARING SIMULATION MODEL (BSSM)

## A. OVERVIEW

The Battlegroup Sparing Simulation Model (BSSM) is an object-oriented computer simulation written in MODSIM. It is a discrete-event model that simulates weapon system failures at the component level. The structure of the weapon system under consideration is input into BSSM utilizing its RBD. The RBD breaks the system down into a series of blocks that represent its equipments. These equipment blocks are then broken down further until the system is represented by its individual components, connected through both series and parallel relationships. These relationships allow the model to determine the state of the blocks and ultimately the state of the system at any time during the simulation.

## B. SIMULATION OBJECTS

BSSM uses five types of objects to simulate failures, determine the impacts of those failures and keep track of readiness statistics. These objects act independently and can represent a battlegroup, a ship, a weapon system, a block or a component

### 1. The Block Object

The block object is the basic unit which allows the simulation to maintain the structure of the system. At any given time the state of the system can be evaluated by the state of its subordinate blocks. A block can have only one parent, which must also be a block, but can have any number of sub-blocks and or components that are subordinate to it. There are three different state spaces in which a block may reside in at any point in time, it can be:

- "on" and "operational" where the block is functional and operating at that point in time.
- "off" and "operational" where the block is functional but not operating at that point in time
- "off" and "not-operational" where the block is not functional and thus is not operating at that point in time.

The required number of subordinates for each block to remain operational is stored one of the block's fields, and is set when the block is initiated. This field allows the block to determine its operational state at any time by counting the number of subordinates that are operational at that time. If there is a change in the state of one of its subordinates, that subordinate will notify the block, triggering it to re-determine its operational status and take appropriate action.

### 2. The Component Object

A component object models the basic components that make up the system. The component object inherits the functions and methods of the block object with the exception of the methods that schedule failures and turn the components on and off. The component object also has fields to store additional information. These fields allow the model to determine the component's remaining lifetime, the maintenance capability required to repair the it and the length of time that repair will take. Table 4.1 is a summary of these fields.

| Field | Description | Purpose |
|---|---|---|
| Lifelength | Remaining life of the component (Real) | Component failure is triggered when life-length expires. |
| StockNo | Part number of the component (Integer) | Allows the model to determine stock availability of the failed item. |
| Capability | Ship repair capability. (Boolean) | Allows the model to determine whether or not the repair can be made while at sea. |
| RepairTime | MTTR of the component. (Real) | Allows the model to determine the time to repair when the spare becomes available. |
| TimeToFail | Failure rate of the component (Real) | Allows the model to determine the life-length of an iteration of that component. |

**Table 4.1 Additional Component Fields**

### 3. The System Object

The system object inherits the functions and methods of the block object. It creates the blocks and components that make up the system when it is initiated and keeps track of a ship object as its parent. The system object generates the remaining lifetimes of the components in the system and regenerates failed components after their associated logistics delay has expired. Finally, the system object keeps track of the time it is operational and not operational to be used in the final Ao calculation for the mission cycle.

### 4. The Ship Object

The ship can contain any number of subordinate system objects. The ship object performs three basic tasks for the simulation:

- Maintains the shipboard level inventory.

- Provides its system objects with the appropriate logistics delay when a failure occurs.
- Turns its system objects off and on as the ship pulls in and out of port.
- Allows for the flexibility to create multi-system structures, capturing the interaction between systems with common spares, estimating the overall readiness of a ship.

### 5. The Battlegroup Object

The battlegroup object can hold any given number of ships and is similar to the ship object in that it has its own level of inventory. The battlegroup object is the final clearinghouse for all requisitions that cannot be satisfied onboard a ship object. When this occurs the battlegroup screens its stock and provides the system object the appropriate logistics delay. If the requisition can be filled by a part from the battlegroup inventory, a delay of 48 hours[9] will be returned. Otherwise a delay of 360 hours will be returned reflecting a requisition that has been referred to the wholesale supply system. The battlegroup object controls the simulation, looping the ships through the given mission cycle and stopping the simulation when the desired level of confidence has been obtained.

## C. THE SIMULATION

Prior to running the simulation, the RBD of the system under consideration must be reviewed to determine how the actual structural relationship of the system relates to the block and component structure of the model. A data file is then created in accordance

[9] The 48-hour delay for requisitions that are in stock at the battlegroup level is an estimate of the amount of time required to transport the required part to the requisitioning unit.

with Appendix B. The simple RBD depicted in Figure 4.1 will be the example used in further discussion of the model.

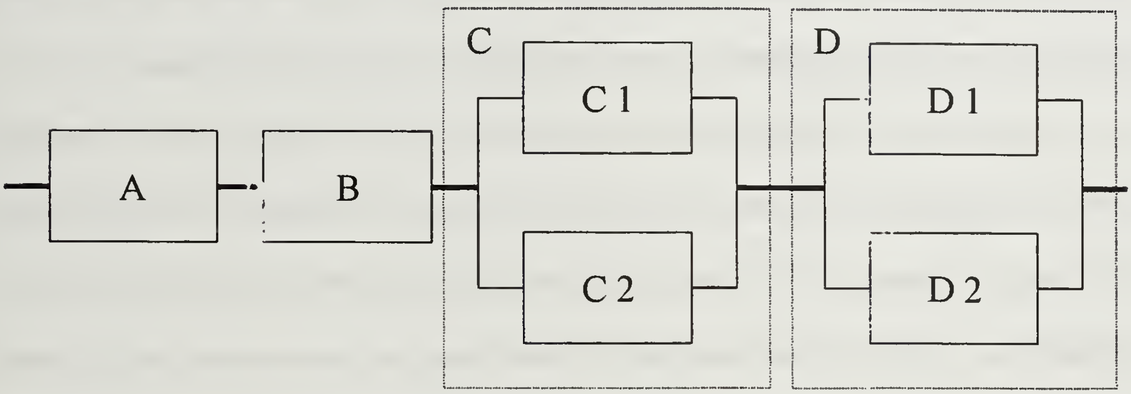


**Figure 4.1 Sample Reliability Block Diagram**

As the model reads the data file it creates the block and component objects that make up the system, setting the appropriate fields to their initial values. After each component is created it also calculates the remaining lifetime of the component in accordance with its MTBF. Once the structure is input, the simulation is started from within the battlegroup object. A recursive function is then activated, turning on the ships, their systems and ultimately the blocks and components that make up these systems. As the components are turned on, they will schedule failure events in accordance with their remaining lifetime. The simulation continues to run for the length of the system's mission cycle.

A failure event occurs when the remaining lifetime of a component expires. This event causes the component to turn itself off, put itself in a non-operational state and notify its parent that it has failed. The parent block then determines its operational status based on the system's RBD. If the component failure results in the failure of the entire block, the block turns itself off, puts itself in a non-operational status and notifies its parent. This process continues up the block structure of the system until either the entire system fails or a block does not fail due to the failure of one of its subordinates.

For example, in Figure 4.1, if component D1 were the first to fail, it would put itself in a non-operational state, then notify block D that it had failed[10]. Block D would then see that component D2 is still operational and therefore conclude that it was still operational. Thus the process would end at block D and no further action would be taken due to the failure of D1. However, if component D2 were to fail prior to the repair of component D1, block D would conclude that it was not operational, place itself in a non-operational status and notify the system of its failure. Since block D is in the critical path of operation for the system, the system would then be forced to turn itself off.

Another action that is initiated when a component fails is the regeneration of the failed component. The process begins with the component notifying the system that it has failed. The system then determines if ship's force is capable of completing the repair, and if so it requests a spare from its ship. The ship will then check to see if a spare is available to replenish the required component. If it is, it provides the system with a shipboard logistics delay time of 2 hours, otherwise it refers the requirement to the battlegroup, which will check its inventory and provide the appropriate delay. After

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[10] This simulation assumes system diagnostics capable of detecting failures in parallel components.

waiting the appropriate delay time the system calculates the repair time of the component using its MTTR; once this time has passed it regenerates the component.

If ship's force is not capable of completing the repair, the system waits until the ship pulls into port, then it calculates and waits the appropriate repair time, regenerating the component after this time has passed.

Once regenerated, the component will change its state to operational and notify the block above it. If the parent block was previously non-operational, the component's regeneration will trigger the block to check its operational status. If the block is now operational it will change its state and notify its parent. This process continues up the structure of the system until either a block is reached that was previously operational or the system changes its state to operational. When the process reaches a block that was previously operational, the subordinate will check to see if its parent is also operational. If so it will turn itself on and start a recursive process that will turn on all of its subordinate blocks and components. Using the previous example, when component D1 was regenerated it would notify block D. Assuming block D was in an operational and operating status it would turn component D1 on and the process would be complete. This process continues throughout the mission cycle of the system, during which time each block (including the system itself) keeps track of its uptime and downtime. These figures allow the system to calculate its availability at the end of each mission cycle. The result is then placed in a statistical object to determine the average system availability. The statistical object also calculates a 95% confidence interval based on the normal distribution.

## D. MODEL VALIDATION

The battlegroup simulation model was validated in two stages. The first stage consisted of a series of BSSM runs for a small system whose readiness could be manually calculated. For the second stage, a comparison was made between budget to readiness curves created for the CES using Tiger and BSSM.

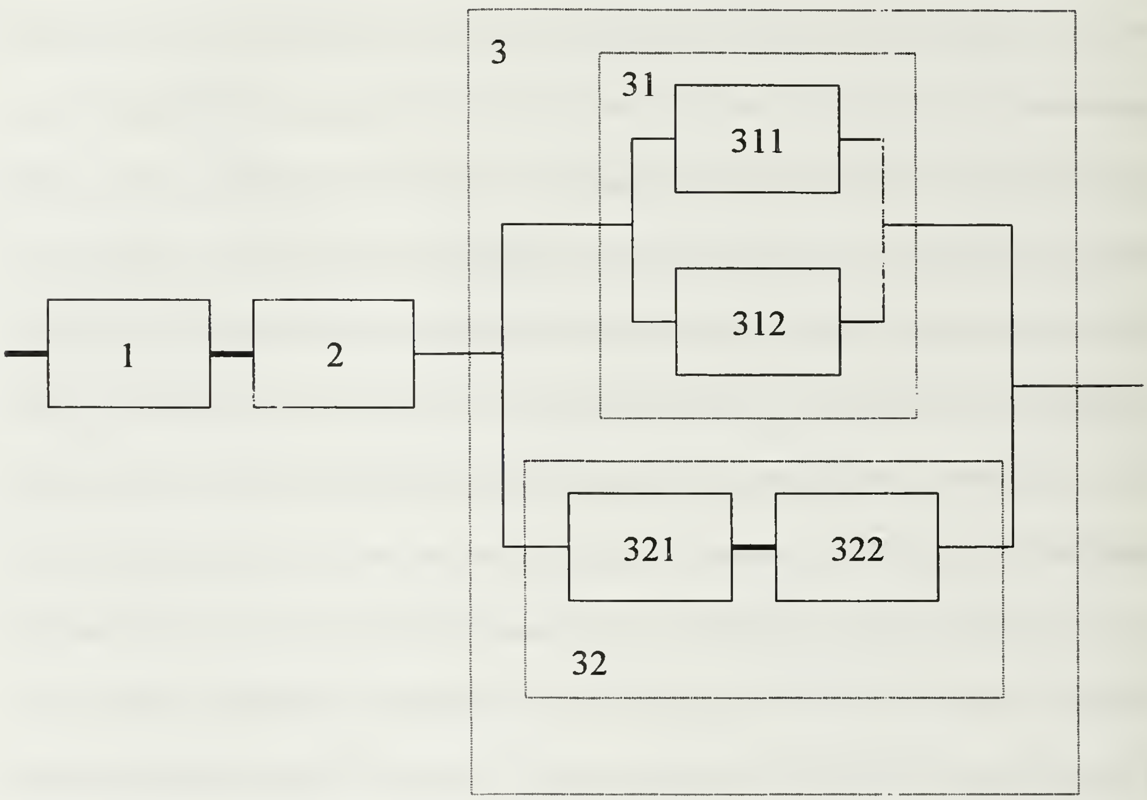


**Figure 4.2 BSSM Validation System**

The first stage began with the development of the small system shown in figure (4.2) consisting of three blocks (1, 2 and 3) on the reliability line. Blocks 1 and 2 consist of only one component, while block 3 has two sub-blocks (31 and 32). Block 31 consists of two components (311 and 312) which are connected in parallel while block 32 consists of two components (321 and 322) which are connected in series. A data set was then built for the system in accordance with Appendix (B) and loaded into the BSSM. The BSSM was then modified to run with output statements showing the time of each component failure and regeneration. The model was then run and the figures produced were used to calculate system readiness manually. A comparison was then made between manual calculation and the readiness figures produced by the model. As the two figures matched exactly, the first stage of the validation was considered to be complete. For the second stage of the validation, a budget-to-readiness curve was created for CES. The curve was produced by plotting the points from an OPT listing created by NAVSEALOGCEN using the RBS methodology discussed in Chapter III. The BSSM was then used to produce a similar curve, the two curves are shown in Figure (4.3). The points of the RBS OPT are depicted as squares while the points of the BSSM OPT are depicted as circles. As both of these models are simulations it is understood that the results would not match exactly, however, since both models produced similar results throughout the spectrum of the OPT listing, the BSSM was considered to be an accurate measure of system readiness for a given level of sparing.

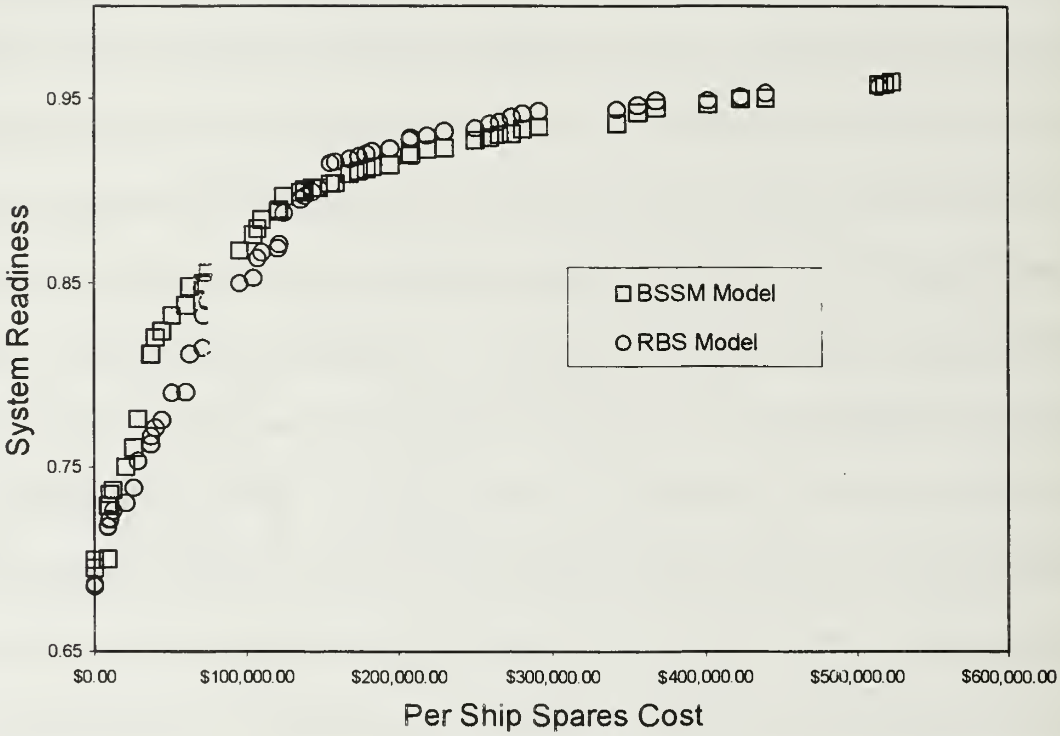


**Figure 4.3 RBS vs. BSSM Single Ship Budget to Readiness Curves**

# V. APPLICATION OF BSSM TO CES

## A. METHODOLOGY

In the previous chapter, BSSM was used to create a single ship budget-to-readiness curve. To be consistent in the comparison of the battlegroup and single-ship inventory strategies, this curve will serve as the baseline, representing the single-ship sparing method in practice today. The BSSM OPT list for a single-ship strategy is included as Appendix (C), reflecting the level of sparing required to achieve 95% Ao.[11]

A data set for a battlegroup of 10 identical ships was then created to be the input model for a series of runs of the BSSM model. For the initial run, the battlegroup level of inventory had no spares, while each of the 10 ships carried a full complement of the spares required achieve 95% Ao. For each subsequent run, the lowest ranking (in accordance with Appendix (C)) remaining spare part at the shipboard level was removed from each ship and a single unit of this spare was placed at the battlegroup level. For example, in the second iteration, part number 7019023 was removed from each of the 10 ships and a single unit of part number 7019023 was placed at the battlegroup level. This process continued throughout the spectrum of Appendix (C), the result being the creation of a battlegroup OPT listing that is included as Appendix (D). These data were used to create a Battlegroup Budget to Readiness curve, which is shown with the single ship budget to readiness curve in Figure 5.1. In this Figure, the battlegroup-sparing budget-to-readiness curve is depicted by squares while circles depict the single-ship curve.

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[11] The Mission Need Statement (MNS) of CES requires 95% system availability.

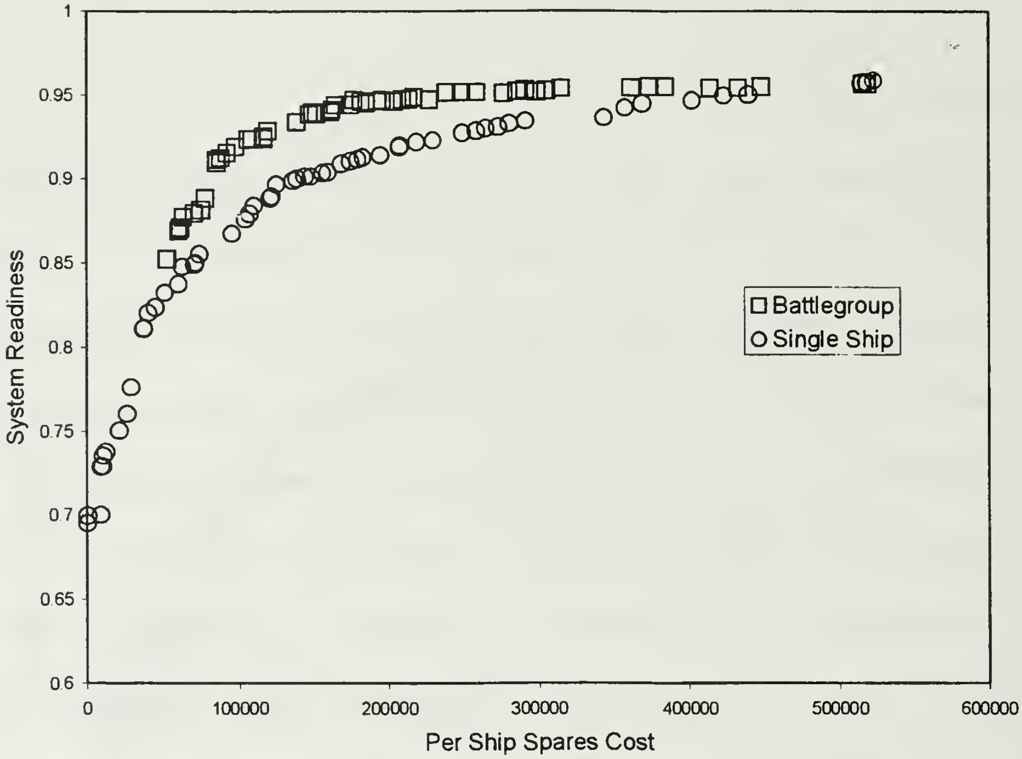


**Figure 5.1 Battlegroup vs. Single Ship**
**Budget to Readiness Curve**

## B. ANALYSIS

Since a simulation produced the points in Figure 5.1, they are only estimates of what the actual readiness would be for that level of sparing[12]. To combine these points into a more precise estimate of the budget and readiness impacts of each inventory strategy, regression analysis was performed on each set of points.

A system's Ao is limited by 100% readiness. Readiness should also monotonically increase as the spares budget increases, making the budget-to-readiness curve act a lot like a Cumulative Density Function (CDF). The Logistics CDF is shaped

[12] Using one thousand iterations, the average variability of the BSSM estimate was plus or minus .003.

in a manner similar to that of both data sets, making it a natural candidate to fit the data. Equation 5.1 is the basic form of the Logistics CDF, while Equation 5.2 is the form used to fit the data. It should be noted that (a) is the intercept of the curve on the Ao axis and should equate to the system's Az while (b) is the maximum increase in system Ao, thus (a + b) should equate to the system's Ai.

$$\mathbf{F(x) = 1 - \frac{1}{1 + e^{(-x)}}} \tag{5.1}$$

$$\mathbf{y = a + \frac{b}{1 + e^{(-(x-d)*c)}}} \tag{5.2}$$

Utilizing SPLUS© software and a function created by Professor Sam Butterey of the Naval Postgraduate School, the data was fit the form of Equation 5.2. The results of this function were Equations 5.3 and 5.4, which fit the single ship and battlegroup sets of data respectively. The variable x in these Equations is equivalent to the cost of each inventory strategy. Figure 5.2 is a graphical depiction of these curves with their respective data sets.

$$\mathbf{Ao = .696 + \frac{.283}{1 + e^{-(\log(x)-11.0)*1.06}}} \tag{5.3}$$

$$\mathbf{Ao = .69 + \frac{.267}{1 + e^{-(\log(x)-10.7)*2.06}}} \tag{5.4}$$

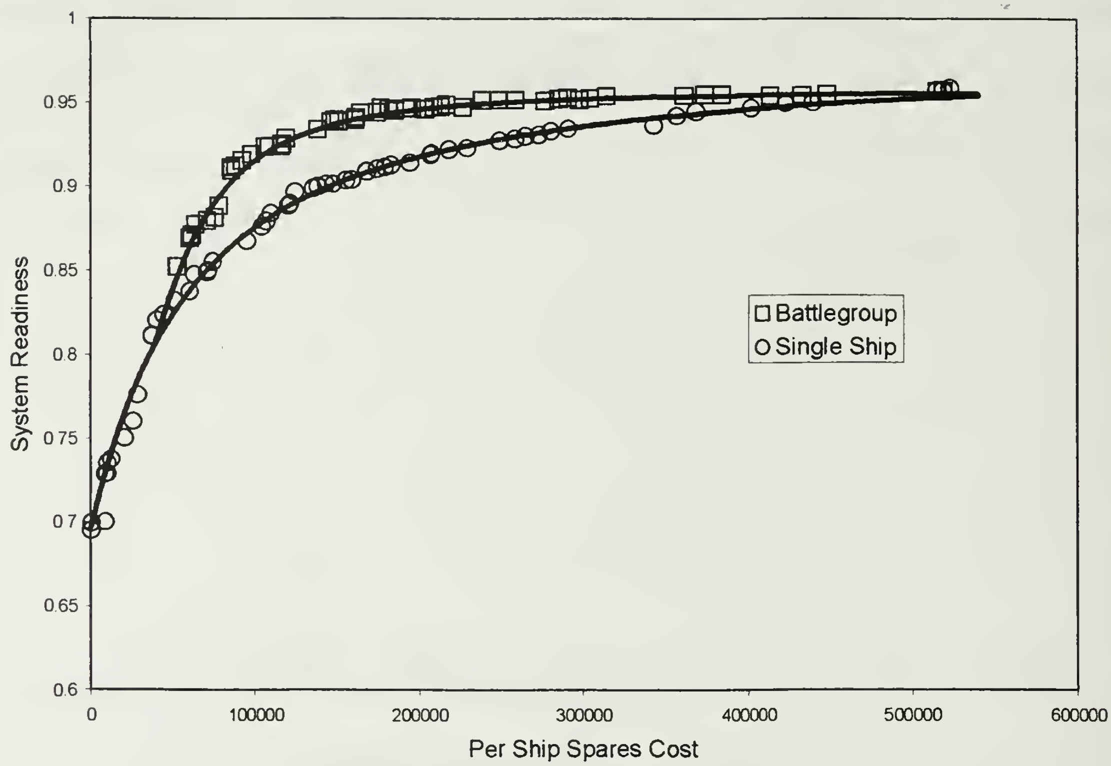


**Figure 5.2 Battlegroup and Single-Ship Data with Fitted Curves**

Having fit the two data sets to Equations 5.3 and 5.4, it is simple to compare the impacts of the two inventory strategies. Solving each of them for the 95% Ao requirement yielded budget requirements of $463,804.70 for the single ship strategy and $256,472.40 for the battlegroup strategy, an inventory savings of nearly 50% per ship. Multiplying this cost savings of $207,332.30 per ship over the expected number of installs, 146 in this case, [Mr. Jeff Hoare, 13 August 1997] indicates that a total cost savings of over $30 million could be achieved utilizing the battlegroup sparing inventory strategy.

This, however, is only one of many possible inventory strategies that could achieve 95% Ao. Increasing the range and depth of the battlegroup inventory would reduce the inventory requirement for the individual ships, but it isn't clear how far should this be taken. Ideally, there should be some policy for determining the level of sparing each ship must have. Given this policy, the battlegroup inventory could be modified to meet the system Ao requirement.

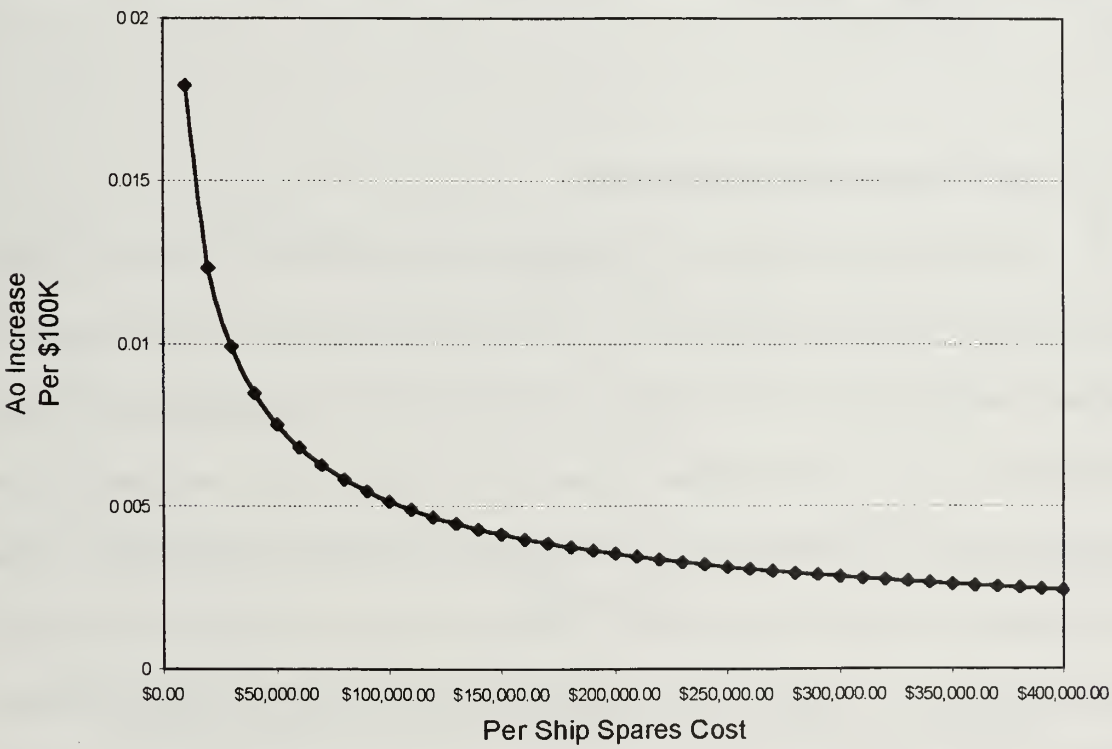


**Figure 5.3 Marginal Increase to System Readiness**

For example, taking the derivative of Equation 5.3 yields the marginal increase to readiness of each additional dollar spent on the shipboard inventory. Figure 5.3 shows this derivative throughout the relative budget range. If shipboard sparing was stopped when the marginal increase in system readiness per $100,000 fell below .005[13], the per ship sparing budget would be reduced to a little over $100,000. The battlegroup inventory could then be augmented in order of the system's OPT list until the system reached 95% Ao. In the case of CES, this policy resulted in a shipboard inventory valued at $121,162 and a battlegroup inventory valued at $526,641, yielding a total cost of $177,803 per ship, a savings of over $286,000 from the original single ship strategy. The recommended battlegroup and shipboard level inventory lists are included as Appendix (E).

## C. VARYING BATTLEGROUP SIZE

The final point of interest in the battlegroup-sparing question is the rate at which an increase in the size of a battlegroup would reduce the effectiveness of the strategy. As the fleet commander may want to deploy more than 10 ships to a geographic area, he/she would need to know the readiness impacts of additional ships competing for the battlegroup spares. The BSSM was used to provide an answer for this question. Using the inventory levels from Appendix (E), additional runs of the BSSM were conducted, varying the number of ships in the battlegroup from 5 to 40. The resulting readiness estimates are shown in Figure 5.4. As these points appeared to have a linear relationship, a linear regression was performed and included in the figure. As expected, system readiness decreased with an increase in battlegroup size. However this decrease in readiness occurred at a rate of only .03% per ship, proving battlegroup sparing to be not only a low cost sparing alternative, but a flexible one as well.

[13] This value was set arbitrarily by the author as an example of the proposed policy change.

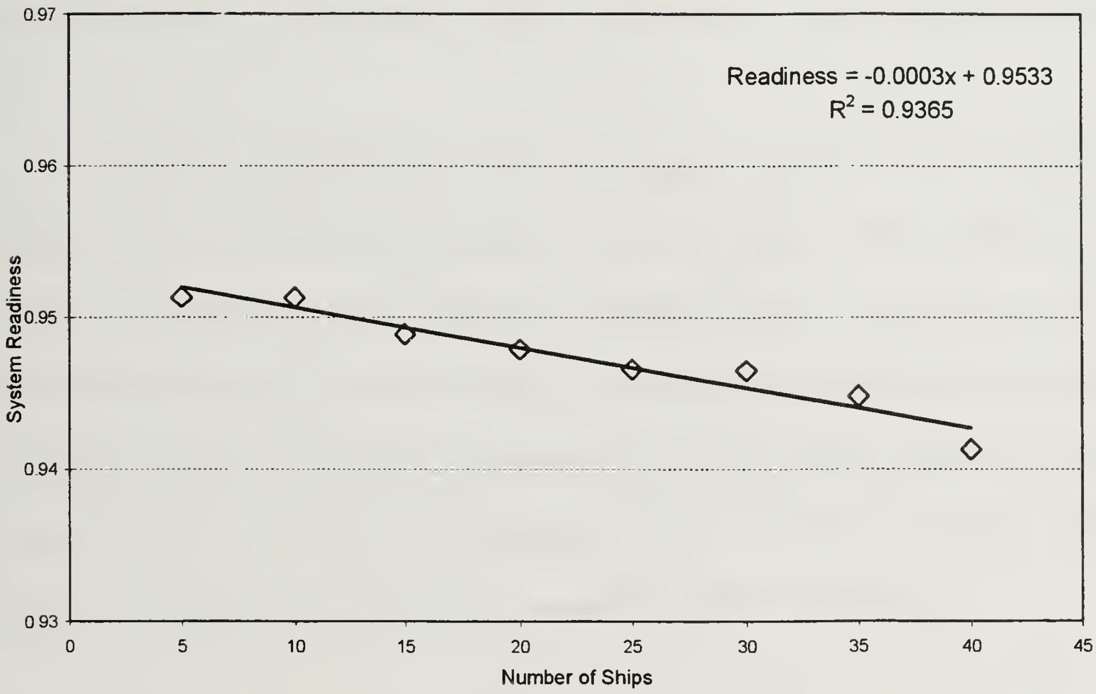


**Figure 5.4 Effect of Varying Battlegroup Size on System Readiness**

# VI. DISCUSSION/RECOMMENDATIONS

In summary, this thesis has accomplished three separate tasks. First, it has uncovered weaknesses in the RBS techniques currently used by the U.S. Navy. Second, it developed a model to evaluate the impacts of battlegroup sparing. Finally, it used this model to show that battlegroup sparing is an inventory option that, for some weapon systems, can achieve a desired level of system readiness at a greatly reduced inventory cost.

It should be noted that this inventory strategy is not suited for all shipboard weapon systems. The cost of obtaining RBS data for the Navy's older systems and the variation in configuration from platform to platform of other systems do not lend themselves to this type of inventory strategy. The cost of creating this data and the fact that shipboard spares have already been procured for these systems minimizes the real savings that could by achieved by utilizing this strategy. There are however, a large number of systems that meet the criteria discussed in Chapter I of this thesis.

## A. WEAKNESSES OF RBS UNCOVERED

Over the course of the RBS discussion in this thesis, several weaknesses were uncovered involving the current process. The weaknesses found concerning ACIM were:

1. Components are considered to be connected in series.
2. Calculations are based on steady-state conditions.
3. Failures occur as a Markov Process.

The first two weaknesses are challenging problems and ACIM may be the closest we can get to a closed form solution. Future studies should attempt to measure the impact of these assumptions to determine the necessity of pursuing these questions further. The third weakness, however, could be corrected by considering the failures of components to be an Alternating Renewal Process (ARP). Utilizing an ARP instead of the current Markov Process would allow the model to account for the component downtime that is involved in every failure.

The weakness noted concerning Tiger involved the manner in which stopping conditions were set. A change in the method in which Tiger keeps its system availability statistic would provide a good solution to this problem. The statistic should be changed so that system availability is calculated at each iteration of the model. These figures could then be used not only to determine overall system availability but also a standard error of the estimate. Tiger could then be modified to stop running once the standard error was within some predetermined tolerance level. This method would provide the user with a consistent level of accuracy and minimize excessive Tiger runs on a given set of data.

## B. FLEET IMPLEMENTATION

Upon measuring the impacts of the battlegroup sparing, it becomes necessary to develop a plan to successfully implement the strategy. This critical link to the successful implementation of battlegroup sparing is an understanding between a system's program office and the type commanders who will be deploying this system. The type commander would need to agree to allow the program office to outfit its ships to some level below the specified Ao goal. In return, the program office would provide the type commander with battlegroup level pack-up kits that would allow the type commanders to utilize battlegroup sparing to meet the system's Ao goal. In the case of CES, the type commander must agree to accept the program office providing initial spares funding to its ships that would only achieve 93% shipboard Ao. In return, the program office can provide the type commander the initial spares to set up pack-up kits that will increase the Ao of deployed CES units to 95%.

## C. TOPICS FOR FURTHER STUDY

This thesis has developed, validated and utilized the BSSM model to better understand the relationship between cost and readiness when a battlegroup sparing inventory strategy is used. It has also raised questions concerning the RBS methodology currently in use that should be addressed in further studies. Possible topics for further study include the following:

1. Determining the impacts of using an Alternating Renewal Process versus a Markov Process to calculate the expected number of demands in ACIM.
2. Studying the impacts of modifying the statistics used in Tiger to change the stopping criteria of the model.

Though not included in this thesis, the BSSM model is available for any further studies in this area and will be provided on request from the author.

## APPENDIX A: COOPERATIVE ENGAGEMENT SYSTEM (CES) RELIABILITY BLOCK DIAGRAM (RBD)

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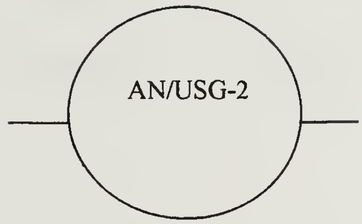
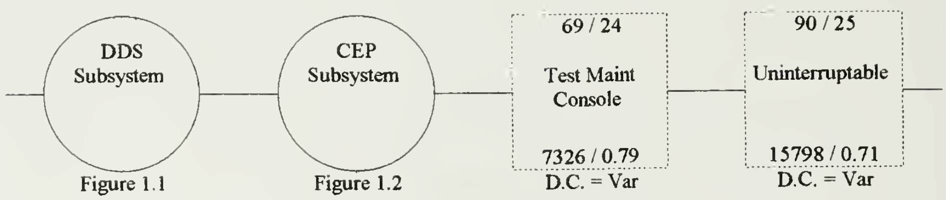


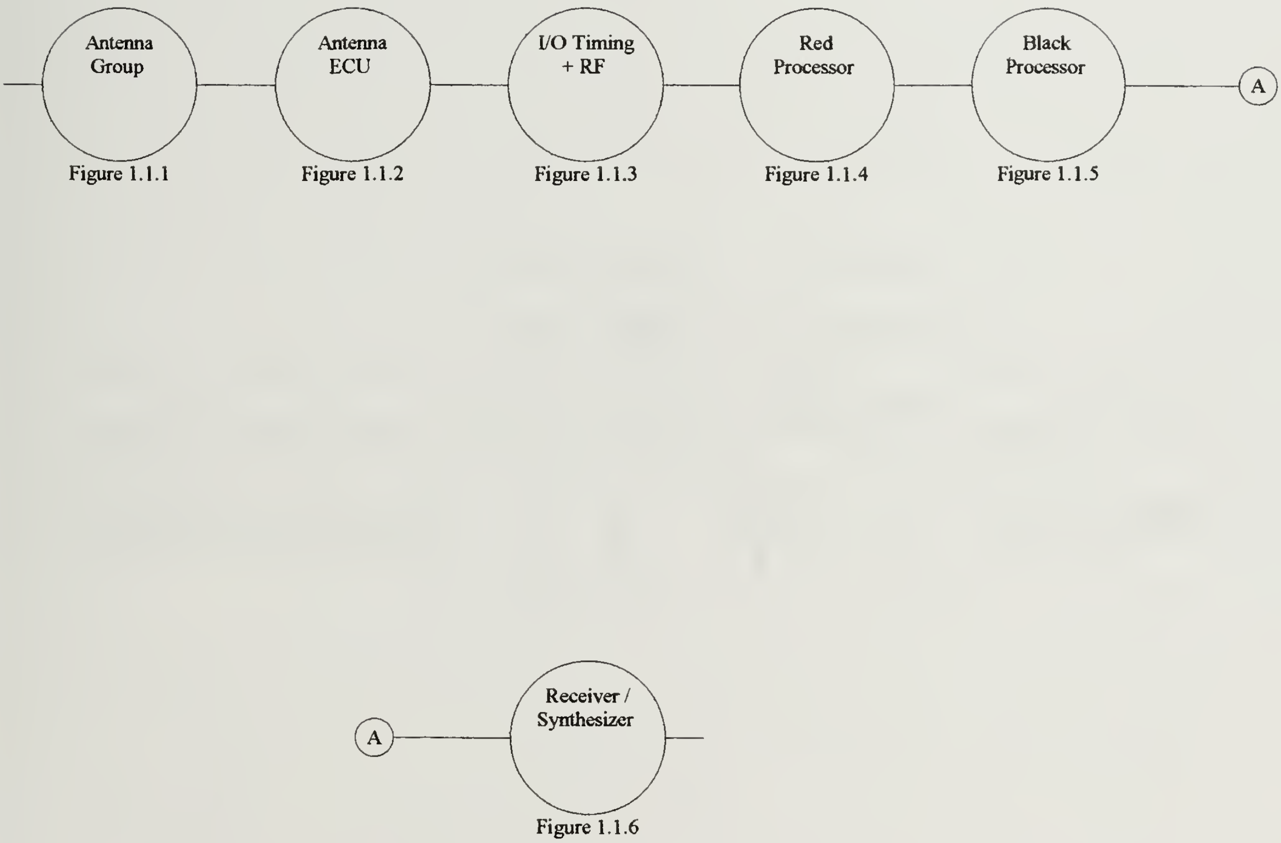
# AN/USG-2 CEC Ver F

## Figure 1 - AN/USG-2



# AN/USG-2 CEC Ver F

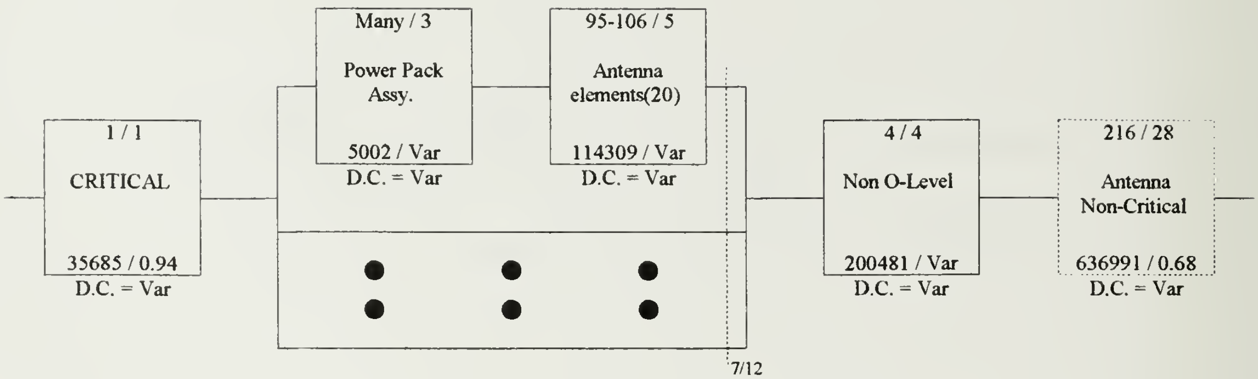
## AN/USG-2
## Figure 1.1 - DDS Subsystem




Prepared By B.Lohr & Co
Organization NSLC
Approved by Date
Version

# AN/USG-2 CEC Ver F

AN/USG-2
DDS Subsystem
Figure 1.1.1 - Antenna Group



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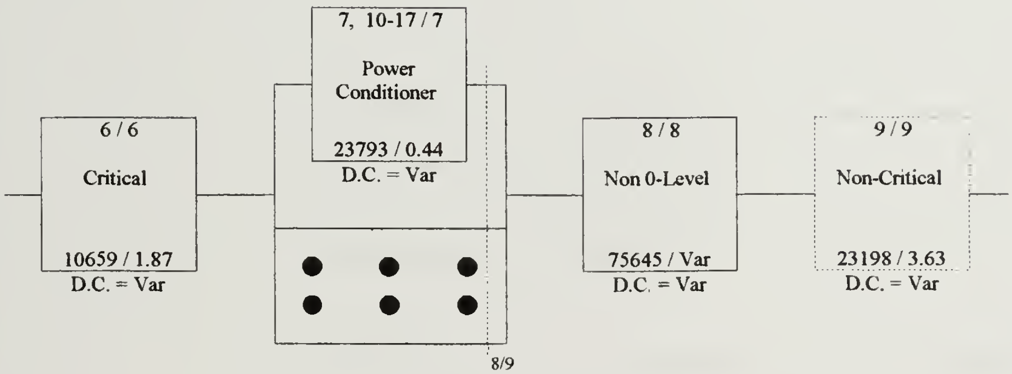
AN/USG-2
DDS Subsystem
Figure 1.1.2 - Antenna ECU

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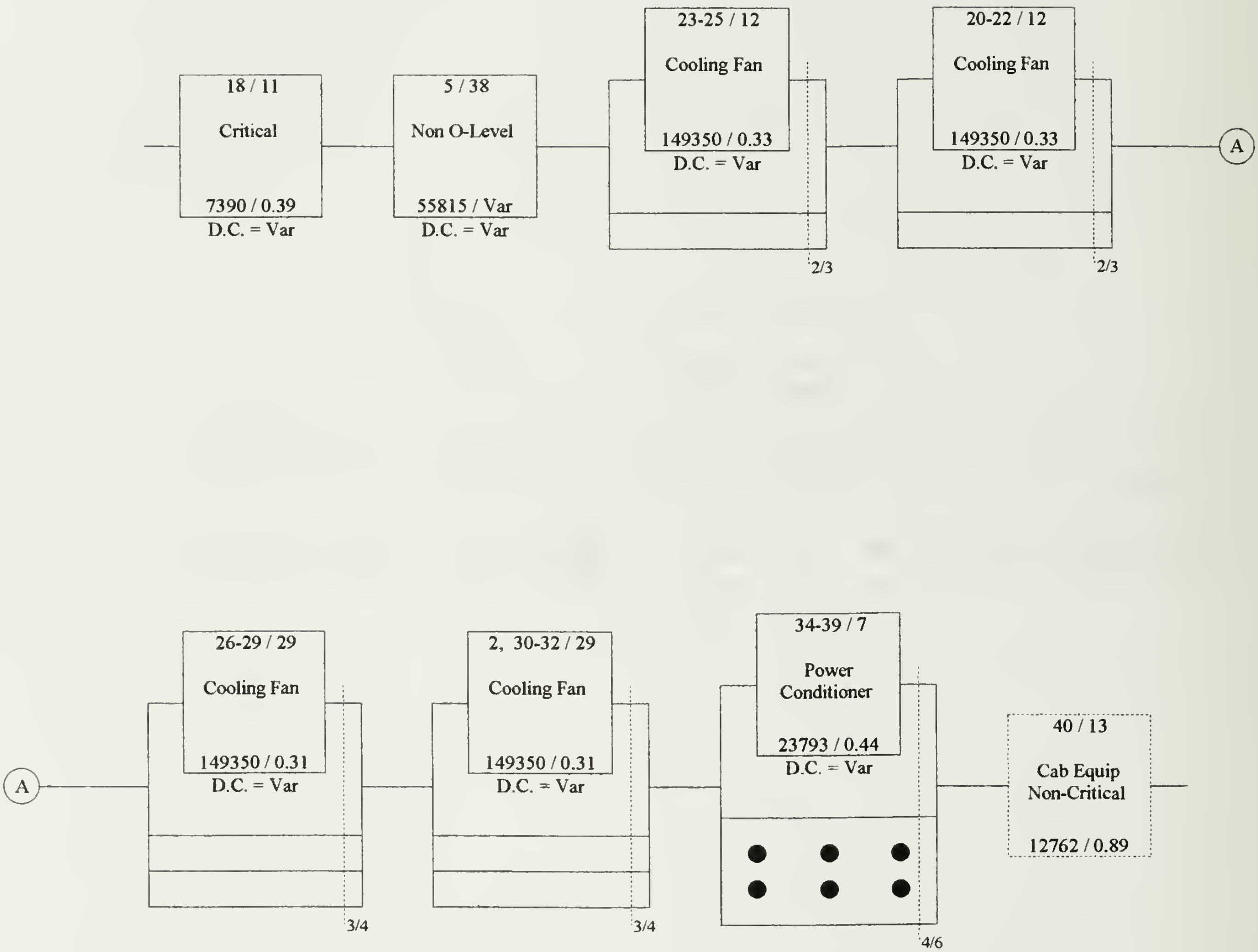
## AN/USG-2 CEC Ver F

AN/USG-2
DDS Subsystem
Figure 1.1.3 - I/O Timing + RF

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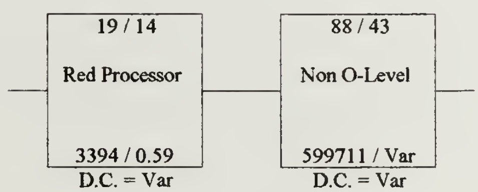
## AN/USG-2
## DDS Subsystem
## Figure 1.1.4 - Red Processor

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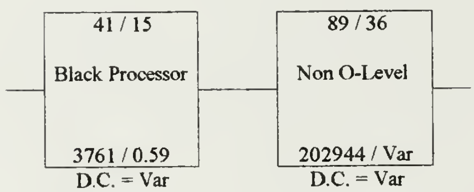
# AN/USG-2 CEC Ver F

AN/USG-2
DDS Subsystem
Figure 1.1.5 - Black Processor

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AN/USG-2
DDS Subsystem
Figure 1.1.6 - Receiver / Synthesizer

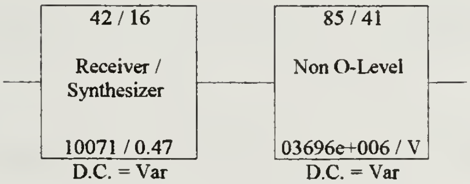


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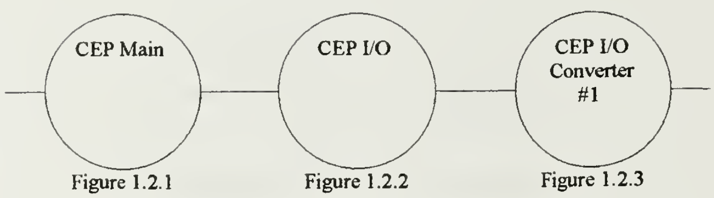
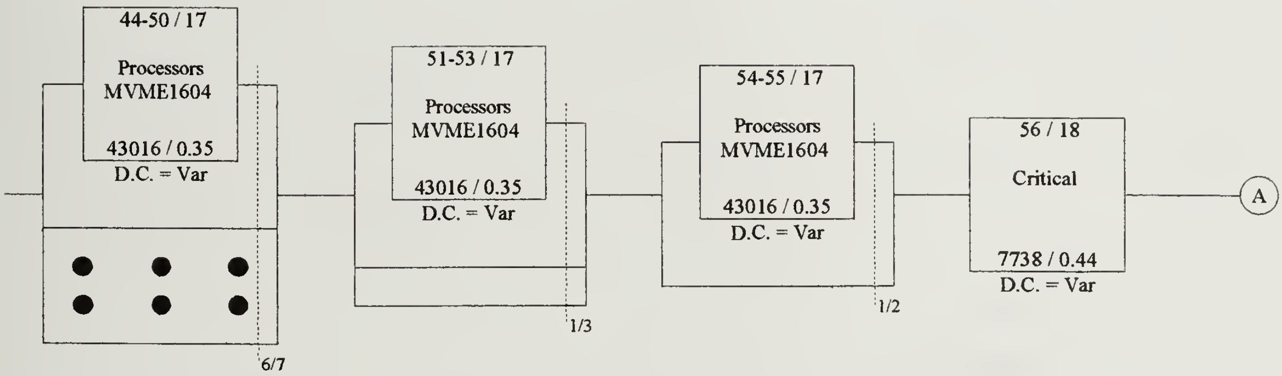
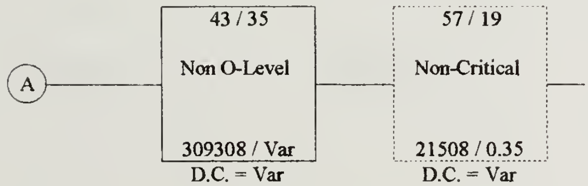
Figure 1.2 - CEP Subsystem



# AN/USG-2 CEC Ver F

## AN/USG-2
## CEP Subsystem
## Figure 1.2.1 - CEP Main

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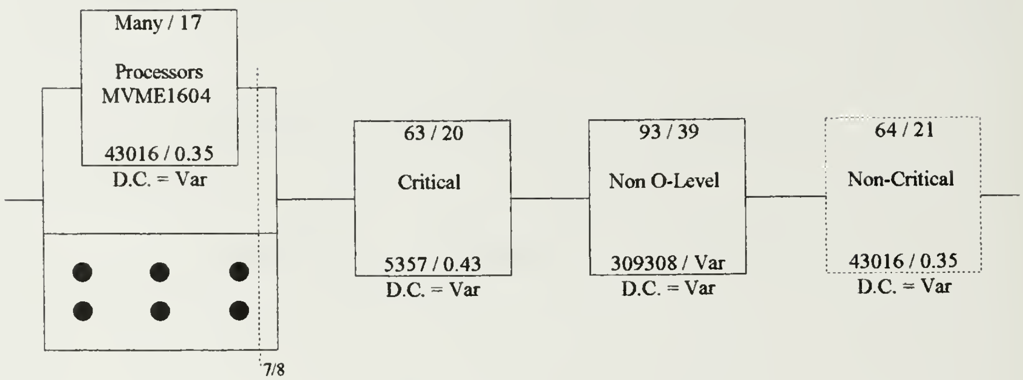
# AN/USG-2 CEC Ver F

AN/USG-2
CEP Subsystem
Figure 1.2.2 - CEP I/O

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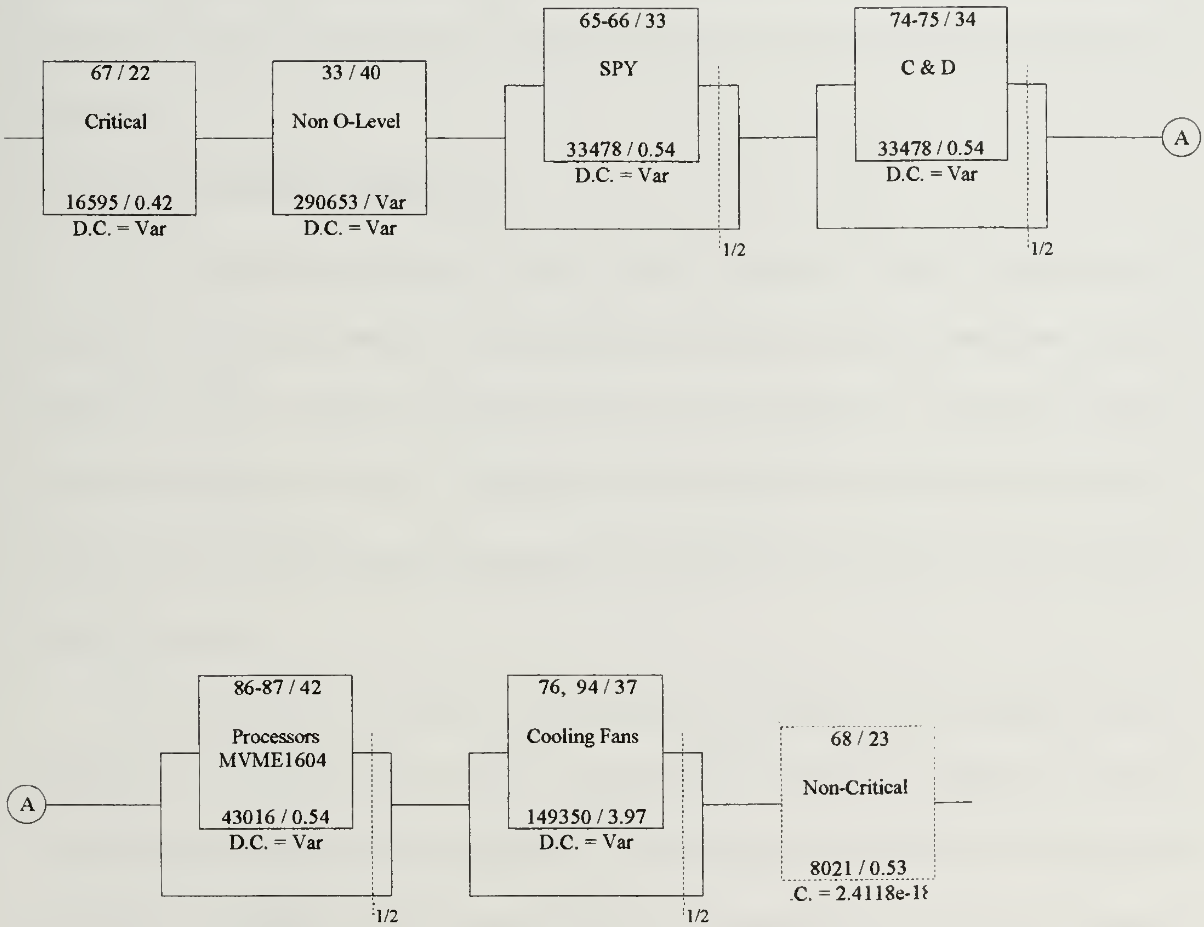
| Version |

# AN/USG-2 CEC Ver F

## AN/USG-2
## CEP Subsystem
## Figure 1.2.3 - CEP I/O Converter #1

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## APPENDIX B: Battlegroup Sparing Simulation Model Users Guide

The Battlegroup Sparing Simulation Model (BSSM) is an object-oriented computer simulation written in MODSIM. The model is estimates the expected readiness of multiple weapon systems in a multiple ship environment using a multi-echelon inventory strategy. The model requires a battlegroup timeline, shipboard and battlegroup inventory lists and a main input file which creates the ships and weapon systems in the battlegroup.

### A. BATTLEGROUP TIMELINE

The mission requirements of a ship's systems change as the ship moves from an at sea period to an in port period. The battlegroup timeline file inputs these times into the battlegroup object to allow it determine the time for its ships to make these changes during the deployment cycle. As a ship moves from an at sea period to an in port period, or vice versa, the ship changes the requirements placed on its system's to be considered in an "up" status.

The initial entry of the file is the total number of mission cycle changes that will take place in the deployment cycle. The remainder of the file consists of a column representing the times the ships are to be at sea and a column for the times the ships will be in port. All entries are in hours and must be integers. The file should be named timeline.txt and placed in the same directory as the main BSSM program.

### B. BATTLEGROUP/SHIP INVENTORY

The battlegroup and ship inventory files are listings of the spare parts that are held at the battlegroup and shipboard levels of inventory. The initial entry of each file is the total number of parts that will be in that inventory. Following the initial entry, the remainder of the file is separated into two columns. The first column is a listing of part numbers; these must be alphanumeric values. The second column is the allowance quantities that correspond to the part numbers in the first column; all values must be integers. These files should be named battle.txt and ship.txt respectively and placed in the same directory as the main BSSM program.

## C. MAIN INPUT FILE

The main input file creates the ships and their systems, which are being simulated. This file is separated into three sections. The first section builds the battlegroup, the second builds the ships and the third builds the weapon systems. The system depicted in Figure B-2 will be used to demonstrate this process.

The battlegroup section consists of the number of ships in the battlegroup, the battlegroup logistics delay time, the wholesale logistics time and the battlegroup stock replenishment time. All entries in the battlegroup section must be integers. Assuming the battlegroup consists of three ships and the logistics delays discussed in this thesis, the first entries of the input file are 3, 48, 360, and 720.

The next section builds the ships within the battlegroup. It consists of the number of systems on each ship, the shipboard logistics delay time and the shipboard stock replenishment time. All entries in the battlegroup and ship sections must be integers. Assuming we are modeling one weapon system per ship the next entries in the input file are 1, 2, and 720.

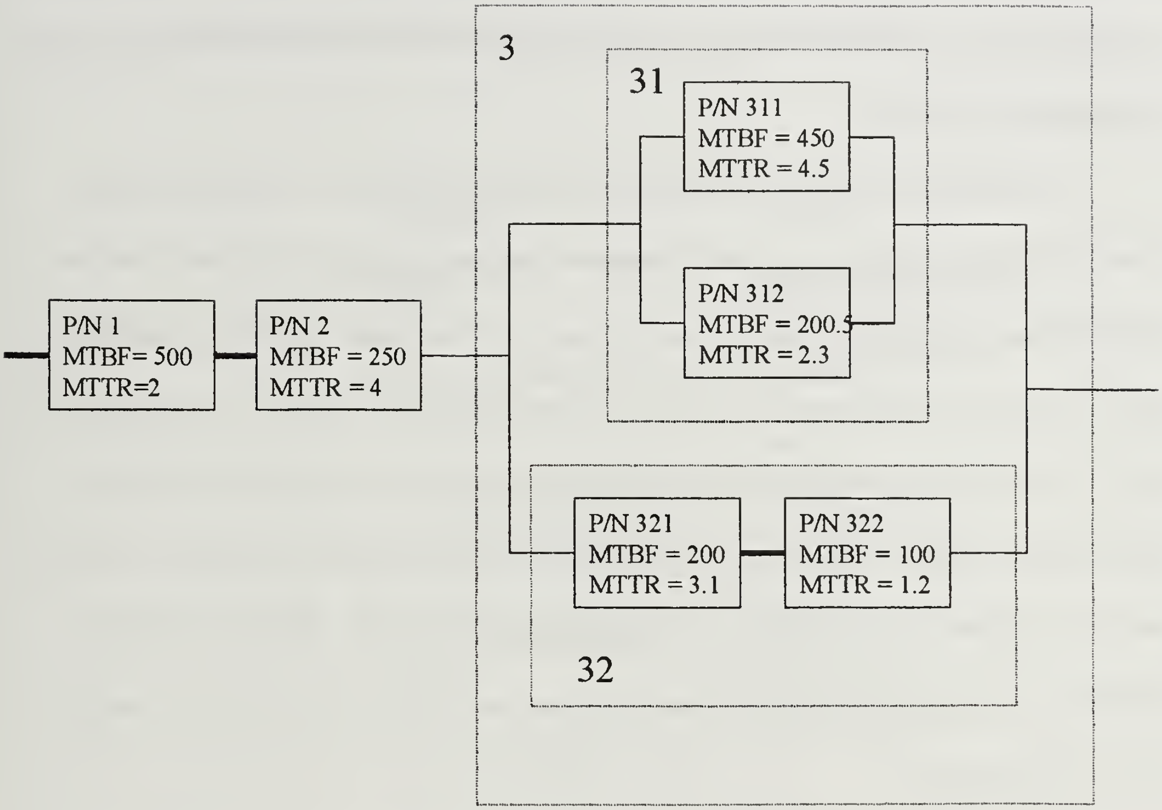


**Figure B-1 System Example**

The third and final section builds the system. It begins by building a system object. The system object then creates its equipment blocks, which continue to create their subordinate blocks and components as they are created. The process begins with the creation of the system.

The system is a block itself and thus uses the same instantiation method as the block object. The required fields are the number of subordinate components, the number of subordinates required to operate and the number of subordinate blocks. Using Figure B-1, there are three subordinates to this system, two are components and the other is a block. All three are required for the system to operate therefore the next three entries to the input file are 2, 3 and 1. This would create two components and one block subordinate to the system.

A component object also inherits the instantiation method of the block object. Thus the creation of the first of these component objects would first require the number of subordinate components, the number required and the number of subordinate blocks. Since we are at the component level there are no subordinates, making these entries 0, 0 and 0. The component object also calls another method to set values to its additional fields, which are its part number, MTBF and MTTR. Thus the next entries are 1, 500.0 and 2.0. The part number entry must be alphanumeric while the MTBF and MTTR entries must be real numbers. The second component would be created by the entries 0,0,0,2, 250.0 and 4.0.

The next step of the input file would create block three of our sample system. This block consists of two subordinate blocks and requires that only one of these blocks be operational. Thus the next entries in the input file would be 0, 1, 2. These entries would create two additional blocks (31 and 32). Block 31 consists of two components that are connected in parallel, thus only one of them has to be operational for the block to continue to be operational. Thus the next entries would be 2, 1, 0. The subordinate components would then be created with the following entries: 0, 0, 0, 311, 450.0, 4.5, 0, 0, 0, 312, 200.0, 2.3. Block 32 consists of two components that are connected in series. Since both are required to maintain the block, the next entries would be 2, 2, 0. The subordinate components would then be created by the following entries: 0, 0, 0, 321, 200.0, 3.1, 0, 0, 0, 322, 100.0, 1.2. Following the completion of the system, the next ship would be created and the process would repeat itself until all the ships in the battlegroup were created. The final input file for the example shown in Figure B-2.

| Input File | | | | | | Comments |
|---|---|---|---|---|---|---|
| 3 | 48 | 360 | 720 | | | Initiates Battlegroup |
| 1 | 2 | 720 | | | | Intiates Ship 1 |
| 2 | 3 | 1 | | | | Creates the System |
| 0 | 0 | 0 | 1 | 500.0 | 2 | Component 1 |
| 0 | 0 | 0 | 2 | 250.0 | 4 | |
| 0 | 1 | 2 | | | | Block 3 |
| 2 | 1 | 0 | | | | Block 31 |
| 0 | 0 | 0 | 311 | 450.0 | 4.5 | Component 311 |
| 0 | 0 | 0 | 312 | 200.0 | 2.3 | Component 312 |
| 2 | 2 | 0 | | | | Block 32 |
| 0 | 0 | 0 | 321 | 200.0 | 3.1 | Component 321 |
| 0 | 0 | 0 | 322 | 100.0 | . 1.2 | Component 322 |
| 1 | 2 | 720 | | | | Intiates Ship 2 |
| 2 | 3 | 1 | | | | Creates the System |
| 0 | 0 | 0 | 1 | 500.0 | 2 | Component 1 |
| 0 | 0 | 0 | 2 | 250.0 | 4 | |
| 0 | 1 | 2 | | | | Block 3 |
| 2 | 1 | 0 | | | | Block 31 |
| 0 | 0 | 0 | 311 | 450.0 | 4.5 | Component 311 |
| 0 | 0 | 0 | 312 | 200.0 | 2.3 | Component 312 |
| 2 | 2 | 0 | | | | Block 32 |
| 0 | 0 | 0 | 321 | 200.0 | 3.1 | Component 321 |
| 0 | 0 | 0 | 322 | 100.0 | 1.2 | Component 322 |
| 1 | 2 | 720 | | | | Intiates Ship 3 |
| 2 | 3 | 1 | | | | Creates the System |
| 0 | 0 | 0 | 1 | 500.0 | 2 | Component 1 |
| 0 | 0 | 0 | 2 | 250.0 | 4 | |
| 0 | 1 | 2 | | | | Block 3 |
| 2 | 1 | 0 | | | | Block 31 |
| 0 | 0 | 0 | 311 | 450.0 | 4.5 | Component 311 |
| 0 | 0 | 0 | 312 | 200.0 | 2.3 | Component 312 |
| 2 | 2 | 0 | | | | Block 32 |
| 0 | 0 | 0 | 321 | 200.0 | 3.1 | Component 321 |
| 0 | 0 | 0 | 322 | 100.0 | 1.2 | Component 322 |

**Figure B-2 Sample System Input File**

# APPENDIX C: BSSM SINGLE SHIP OPT LIST

| Equipment | Part Number | System Ao | Unit Cost | Cumulative Cost |
|---|---|---|---|---|
| 0006 | 7019023 | 0.695158 | $ 408.00 | $ 408.00 |
| 0006 | 7020534 | 0.69944 | $ 224.00 | $ 632.00 |
| 0014 | 7017481 | 0.699866 | $ 8,292.86 | $ 8,924.86 |
| 0006 | M81940/4-3 | 0.728684 | $ 100.00 | $ 9,024.86 |
| 0006 | 7020611 | 0.729056 | $ 1,100.00 | $ 10,124.86 |
| 0006 | 7020540 | 0.735131 | $ 224.00 | $ 10,348.86 |
| 0014 | 7017487 | 0.737378 | $ 2,092.35 | $ 12,441.21 |
| 0015 | 7017481 | 0.750183 | $ 8,292.86 | $ 20,734.07 |
| 0011 | 7017720 | 0.76026 | $ 5,175.48 | $ 25,909.55 |
| 0018 | 7017511 | 0.775957 | $ 2,760.20 | $ 28,669.75 |
| 0018 | 7017490 | 0.810896 | $ 8,308.81 | $ 36,978.56 |
| 0022 | 7018431 | 0.811293 | $ 276.69 | $ 37,255.25 |
| 0020 | 7017490 | 0.820291 | $ 8,308.81 | $ 45,564.06 |
| 0018 | 7017505 | 0.823545 | $ 2,798.81 | $ 48,362.87 |
| 0022 | 7018169 | 0.832241 | $ 4,503.90 | $ 52,866.77 |
| 0022 | 7017692 | 0.837537 | $ 6,461.79 | $ 59,328.56 |
| 0020 | 7018152 | 0.847754 | $ 9,189.36 | $ 68,517.92 |
| 0007 | 7017819 | 0.849105 | $ 8,298.78 | $ 76,816.70 |
| 0006 | 7019821 | 0.849977 | $ 500.00 | $ 77,316.70 |
| 0016 | 7017615 | 0.855281 | $ 2,760.00 | $ 80,076.70 |
| 0011 | 7017854 | 0.867366 | $ 21,233.81 | $ 101,310.51 |
| 0006 | 7017750 | 0.875994 | $ 9,006.41 | $ 110,316.92 |
| 0016 | 7017609 | 0.879008 | $ 2,784.46 | $ 113,101.38 |
| 0006 | 7017826 | 0.883884 | $ 2,674.31 | $ 115,775.69 |
| 0015 | 7017688 | 0.888408 | $ 10,789.06 | $ 126,564.75 |
| 0006 | 7019010 | 0.889475 | $ 1,000.00 | $ 127,564.75 |
| 0016 | 7017508 | 0.896652 | $ 2,932.09 | $ 130,496.84 |
| 0017 | 7017664 | 0.898803 | $ 10,955.19 | $ 141,452.03 |

| Equipment | Part Number | System Ao | Unit Cost | Cumulative Cost |
|---|---|---|---|---|
| 0016 | 7017612 | 0.900141 | $ 2,799.00 | $ 144,251.03 |
| 0020 | 7018345 | 0.901278 | $ 5,175.00 | $ 149,426.03 |
| 0006 | 7019338 | 0.901338 | $ 4,200.00 | $ 153,626.03 |
| 0015 | 7017529 | 0.903384 | $ 7,674.48 | $ 161,300.51 |
| 0015 | 7017733 | 0.903822 | $ 3,672.84 | $ 164,973.35 |
| 0007 | 7017747 | 0.9089 | $ 9,208.98 | $ 174,182.33 |
| 0015 | 7017535 | 0.910287 | $ 5,874.36 | $ 180,056.69 |
| 0016 | 7017591 | 0.911495 | $ 4,893.25 | $ 184,949.94 |
| 0014 | 7019037 | 0.91282 | $ 3,750.24 | $ 188,700.18 |
| 0016 | 7017573 | 0.913929 | $ 11,535.56 | $ 200,235.74 |
| 0016 | 7017579 | 0.918943 | $ 12,837.90 | $ 213,073.64 |
| 0006 | 7018895 | 0.919576 | $ 408.00 | $ 213,481.64 |
| 0017 | 7017664 | 0.922063 | $ 10,955.19 | $ 224,436.83 |
| 0014 | 7017496 | 0.922899 | $ 11,084.96 | $ 235,521.79 |
| 0014 | 7017493 | 0.927306 | $ 20,182.81 | $ 255,704.60 |
| 0018 | 7017623 | 0.928503 | $ 9,243.98 | $ 264,948.58 |
| 0016 | 7017588 | 0.930083 | $ 6,236.06 | $ 271,184.64 |
| 0015 | 7017532 | 0.930811 | $ 8,099.68 | $ 279,284.32 |
| 0016 | 7017582 | 0.933085 | $ 7,305.00 | $ 286,589.32 |
| 0016 | 7017585 | 0.934409 | $ 10,609.24 | $ 297,198.56 |
| 0020 | 7017727 | 0.936363 | $ 51,883.00 | $ 349,081.56 |
| 0016 | 7017594 | 0.942227 | $ 13,744.97 | $ 362,826.53 |
| 0016 | 7017576 | 0.944716 | $ 11,444.61 | $ 374,271.14 |
| 0016 | 7017567 | 0.946679 | $ 33,618.00 | $ 407,889.14 |
| 0015 | 7017538 | 0.949497 | $ 21,465.81 | $ 429,354.95 |
| 0016 | 7017570 | 0.950048 | $ 16,472.03 | $ 445,826.98 |

## APPENDIX D: BSSM BATTLEGROUP OPT LIST

| Equipment | Part Number | System Ao | Unit Cost | Per Ship Cumulative Cost |
|---|---|---|---|---|
| 0006 | 7019023 | 0.851976 | $ 408.00 | 52325.116 |
| 0006 | 7020534 | 0.852123 | $ 224.00 | 52692.316 |
| 0014 | 7017481 | 0.852129 | $ 8,292.86 | 52893.916 |
| 0006 | M81940/4-3 | 0.868896 | $ 100.00 | 60357.49 |
| 0006 | 7020611 | 0.869184 | $ 1,100.00 | 60447.49 |
| 0006 | 7020540 | 0.870676 | $ 224.00 | 61437.49 |
| 0014 | 7017487 | 0.871161 | $ 2,092.35 | 61639.09 |
| 0015 | 7017481 | 0.877238 | $ 8,292.86 | 63522.2 |
| 0011 | 7017720 | 0.879649 | $ 5,175.48 | 70985.78 |
| 0018 | 7017511 | 0.881542 | $ 2,760.20 | 75643.71 |
| 0018 | 7017490 | 0.888301 | $ 8,308.81 | 78127.89 |
| 0022 | 7018431 | 0.911328 | $ 276.69 | 85605.82 |
| 0020 | 7017490 | 0.909527 | $ 8,308.81 | 85854.84 |
| 0018 | 7017505 | 0.912391 | $ 2,798.81 | 88373.77 |
| 0022 | 7018169 | 0.915402 | $ 4,503.90 | 92427.28 |
| 0022 | 7017692 | 0.918956 | $ 6,461.79 | 98242.89 |
| 0020 | 7018152 | 0.923513 | $ 9,189.36 | 106513.3 |
| 0007 | 7017819 | 0.92381 | $ 8,298.78 | 108986.5 |
| 0006 | 7019821 | 0.924002 | $ 500.00 | 116455.4 |
| 0016 | 7017615 | 0.92486 | $ 2,760.00 | 116905.4 |
| 0011 | 7017854 | 0.928494 | $21,233.81 | 119389.4 |
| 0006 | 7017750 | 0.933755 | $ 9,006.41 | 138499.8 |
| 0016 | 7017609 | 0.938414 | $ 2,784.46 | 146605.6 |
| 0006 | 7017826 | 0.939424 | $ 2,674.31 | 149111.6 |
| 0015 | 7017688 | 0.938582 | $10,789.06 | 151518.5 |
| 0006 | 7019010 | 0.939594 | $ 1,000.00 | 161228.6 |
| 0016 | 7017508 | 0.940911 | $ 2,932.09 | 162128.6 |
| 0017 | 7017664 | 0.943697 | $10,955.19 | 164767.5 |

| Equipment | Part Number | System Ao | Unit Cost | Per Ship Cumulative Cost |
|---|---|---|---|---|
| 0016 | 7017612 | 0.943915 | $ 2,799.00 | 174627.2 |
| 0020 | 7018345 | 0.946759 | $ 5,175.00 | 177146.3 |
| 0006 | 7019338 | 0.945953 | $ 4,200.00 | 181803.8 |
| 0015 | 7017529 | 0.945021 | $ 7,674.48 | 185583.8 |
| 0015 | 7017733 | 0.946108 | $ 3,672.84 | 192490.8 |
| 0007 | 7017747 | 0.946706 | $ 9,208.98 | 195796.4 |
| 0015 | 7017535 | 0.945862 | $ 5,874.36 | 204084.4 |
| 0016 | 7017591 | 0.947112 | $ 4,893.25 | 209371.4 |
| 0014 | 7019037 | 0.947464 | $ 3,750.24 | 213775.3 |
| 0016 | 7017573 | 0.948455 | $11,535.56 | 217150.5 |
| 0016 | 7017579 | 0.947209 | $12,837.90 | 227532.5 |
| 0006 | 7018895 | 0.951329 | $ 408.00 | 239086.6 |

## APPENDIX E: PROPOSED ALLOWANCE LISTS

Shipboard Allowance List

| Part Number | Quantity | Unit Cost | Cumulative Cost |
|---|---|---|---|
| 7017481 | 2 | $ 8,292.00 | $ 16,584.00 |
| 7017487 | 1 | $ 2,092.00 | $ 18,676.00 |
| 7017490 | 1 | $ 8,308.00 | $ 26,984.00 |
| 7017505 | 1 | $ 2,798.00 | $ 29,782.00 |
| 7017511 | 1 | $ 2,760.00 | $ 32,542.00 |
| 7017514 | 1 | $ 2,747.00 | $ 35,289.00 |
| 7017609 | 1 | $ 2,784.00 | $ 38,073.00 |
| 7017615 | 1 | $ 2,760.00 | $ 40,833.00 |
| 7017664 | 1 | $ 10,955.00 | $ 51,788.00 |
| 7017692 | 1 | $ 6,461.00 | $ 58,249.00 |
| 7017720 | 1 | $ 5,175.00 | $ 63,424.00 |
| 7017750 | 1 | $ 9,006.00 | $ 72,430.00 |
| 7017819 | 1 | $ 8,298.00 | $ 80,728.00 |
| 7017826 | 1 | $ 2,674.00 | $ 83,402.00 |
| 7017854 | 1 | $ 21,233.00 | $ 104,635.00 |
| 7018152 | 1 | $ 9,189.00 | $ 113,824.00 |
| 7018169 | 1 | $ 4,503.00 | $ 118,327.00 |
| 7018431 | 1 | $ 276.00 | $ 118,603.00 |
| 7019023 | 1 | $ 408.00 | $ 119,011.00 |
| 7019821 | 1 | $ 500.00 | $ 119,511.00 |
| 7020534 | 1 | $ 227.00 | $ 119,738.00 |
| 7020540 | 1 | $ 224.00 | $ 119,962.00 |
| 7020611 | 1 | $ 1,100.00 | $ 121,062.00 |
| M-8194043 | 1 | $ 100.00 | $ 121,162.00 |

Battlegroup Allowance List

| Part Number | Quantity | Unit Cost | Cumulative Cost |
|---|---|---|---|
| 7017481 | 2 | $ 8,292.00 | $ 16,584.00 |
| 7017487 | 1 | $ 2,092.00 | $ 18,676.00 |
| 7017490 | 1 | $ 8,308.00 | $ 26,984.00 |
| 7017505 | 1 | $ 2,798.00 | $ 29,782.00 |
| 7017511 | 1 | $ 2,760.00 | $ 32,542.00 |
| 7017514 | 1 | $ 2,747.00 | $ 35,289.00 |
| 7017609 | 1 | $ 2,784.00 | $ 38,073.00 |
| 7017615 | 1 | $ 2,760.00 | $ 40,833.00 |
| 7017664 | 2 | $ 10,955.00 | $ 62,743.00 |
| 7017692 | 1 | $ 6,461.00 | $ 69,204.00 |
| 7017720 | 1 | $ 5,175.00 | $ 74,379.00 |
| 7017750 | 1 | $ 9,006.00 | $ 83,385.00 |
| 7017826 | 1 | $ 2,674.00 | $ 86,059.00 |
| 7017854 | 1 | $ 21,233.00 | $ 107,292.00 |
| 7018152 | 1 | $ 9,189.00 | $ 116,481.00 |
| 7018169 | 1 | $ 4,503.00 | $ 120,984.00 |
| 7018431 | 1 | $ 276.00 | $ 121,260.00 |
| 7019023 | 2 | $ 408.00 | $ 122,076.00 |
| 7019821 | 1 | $ 500.00 | $ 122,576.00 |
| 7020534 | 2 | $ 227.00 | $ 123,030.00 |
| 7020540 | 1 | $ 224.00 | $ 123,254.00 |
| 7020611 | 1 | $ 1,100.00 | $ 124,354.00 |
| M-8194043 | 2 | $ 100.00 | $ 124,554.00 |
| 7017774 | 1 | $ 4,476.00 | $ 129,030.00 |
| 7018924 | 1 | $ 3,700.00 | $ 132,730.00 |
| 7017482 | 1 | $ 74,809.00 | $ 207,539.00 |

Battlegroup Allowance List (Cont'd)

| Part Number | Quantity | Unit Cost | Cumulative Cost |
|---|---|---|---|
| 7017570 | 1 | $ 16,472.00 | $ 224,011.00 |
| 7017538 | 1 | $ 21,465.00 | $ 245,476.00 |
| 7017567 | 1 | $ 33,618.00 | $ 279,094.00 |
| 7017576 | 1 | $ 11,444.00 | $ 290,538.00 |
| 7017594 | 1 | $ 13,744.00 | $ 304,282.00 |
| 7017727 | 1 | $ 51,883.00 | $ 356,165.00 |
| 7017585 | 1 | $ 10,609.00 | $ 366,774.00 |
| 7017582 | 1 | $ 7,305.00 | $ 374,079.00 |
| 7017532 | 1 | $ 8,099.00 | $ 382,178.00 |
| 7017588 | 1 | $ 6,236.00 | $ 388,414.00 |
| 7017623 | 1 | $ 9,243.00 | $ 397,657.00 |
| 7017493 | 1 | $ 20,182.00 | $ 417,839.00 |
| 7017496 | 1 | $ 11,084.00 | $ 428,923.00 |
| 7018895 | 1 | $ 408.00 | $ 429,331.00 |
| 7017579 | 1 | $ 12,837.00 | $ 442,168.00 |
| 7017573 | 1 | $ 11,535.00 | $ 453,703.00 |
| 7019037 | 1 | $ 3,750.00 | $ 457,453.00 |
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